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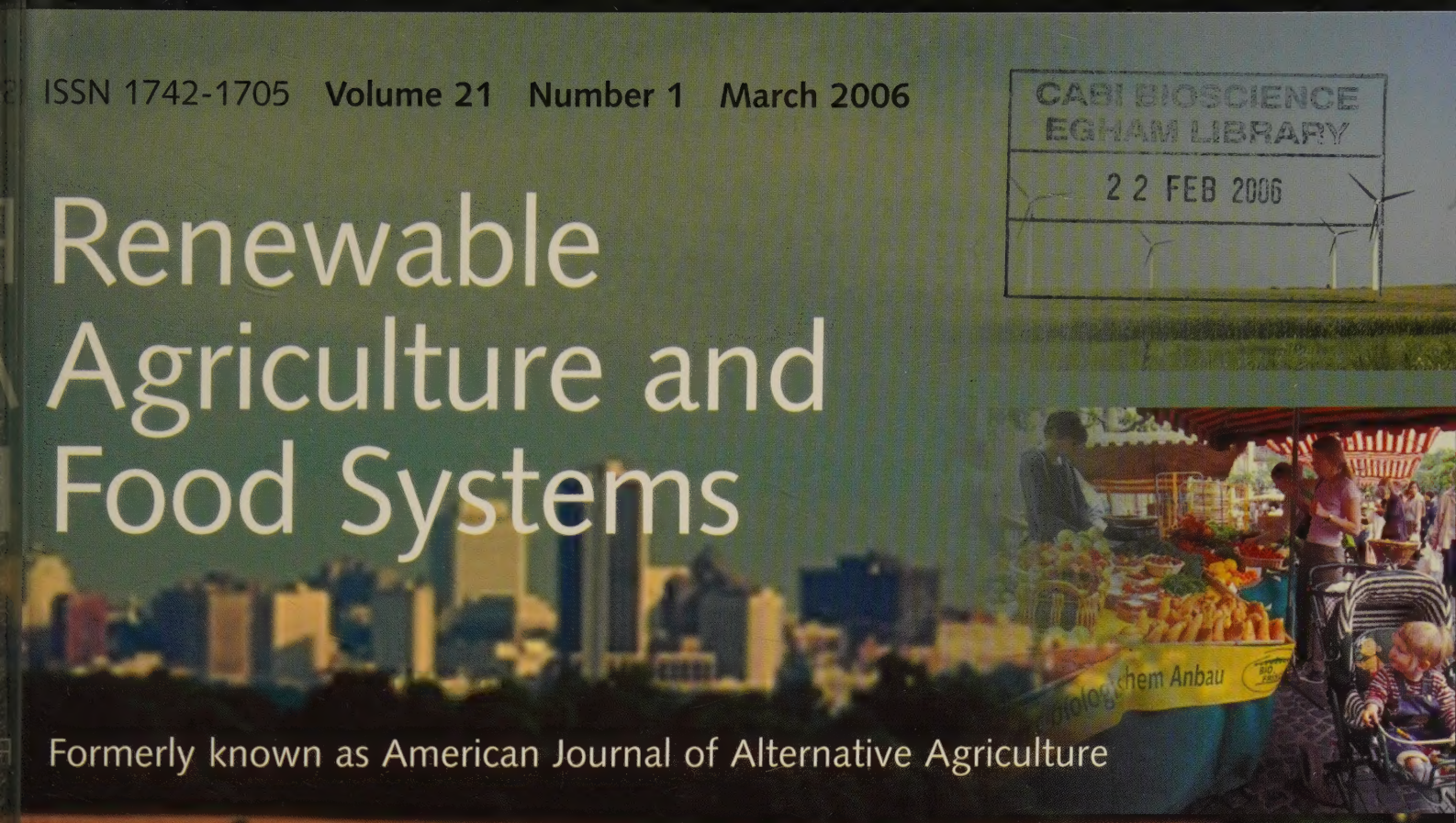

Special Issue

Soil Quality: Tools for Developing Sustainable Management Systems
Special Guest Editors:
Brian J. Wienhold &
Ray R. Weil

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Aims and Scope

Renewable Agriculture and Food Systems provides an international forum for original research and review articles on the biological, physical, social science, and policy aspects of alternative agriculture and food systems, focusing on the effective use of renewable resources and biodiversity in agro-ecosystems. The journal particularly welcomes multidisciplinary, holistic, systems research that addresses the multiple challenge of economically meeting basic human needs for food, fiber, and energy while maintaining essential natural and environmental resources.

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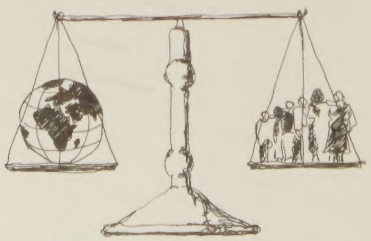

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Renewable Agriculture and Food Systems

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Special Issue
Soil Quality for Identifying Improved Management Systems
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Editorial

Preserving soil and crop resources by increasing cropping intensity and decreasing tillage

Soils perform many essential functions for plant growth, water storage, and water and air quality. Future generations depend on our crop and soil management practices to maintain or improve the soil's ability to perform these essential functions while providing the food and fiber needed by society. Unfortunately, many soils have been degraded[1] because we either did not understand the negative effects of certain management practices or we lacked better alternatives. In recent years, scientific research, farmer innovation, and new commercial technologies have allowed improved soil management in many regions. In spite of this progress, additional improvements in soil management will be required to restore and then maintain the functional capacity of the soil resource.

The Great Plains of Canada and the US is a major agricultural region producing sorghum, corn, wheat, and other small grains. This productive region is also highly susceptible to the vagaries of climate and destructive natural forces, such as those that gave rise to the Dust Bowl in the 1930s. The continental climate of the Great Plains and western Corn Belt is characterized by highly variable precipitation and temperature, both within and among years.

Farmers who settled in this region, utilizing practices developed in more humid regions, experienced a high incidence of crop failure. In order to survive in the harsh, erratic environment of the Great Plains, different management practices were needed. Crop–fallow was developed as a practice to reduce the risk of crop failure due to water stress by allowing soil water to accumulate during the fallow period for use by the subsequent crop. Crop–fallow, using intensive tillage for seedbed preparation and weed control, soon became the dominant practice throughout the region. While the incidence of crop failure declined, the loss of organic matter, susceptibility of soil to wind and water erosion during the fallow period, development of extensive saline seeps, and the need for two growing seasons to produce a crop led many to conclude that crop–fallow was not a sustainable system. As herbicides and minimum tillage implements became available, research was initiated throughout the region to develop more intensive cropping systems that kept the land under crops every year. Initial results from these studies demonstrated that annual yields and economic returns were greater with more intensive cropping[2]. In addition, wind erosion was reduced and precipitation use efficiency increased[3]. The impact of more intensive cropping on the soil resource was difficult to assess as changes in many soil properties occur slowly.

In the late 1970s, the concept of soil quality was introduced[4]. Scientists have developed the soil quality concept into a tool useful in educating people about the relationships between soil properties and the essential functions performed by soils[5]. Soil quality has also developed into a useful concept for land managers to assess their progress toward managing their soils in a suitable manner. Soil quality assessments involve standardized measurement of soil properties that serve as indicators of important soil functions. These soil quality indicators can be used to compare alternative management practices or to monitor changes over time. Efforts are continuing to develop measurement protocols and interpretation tools that land managers and consultants can more easily use.

This special issue includes seven papers that focus on alternative cropping systems in the North American Great Plains. Five of these papers present results from a multi-location, long-term study aimed at improving the soil quality concept as a tool for assessing management and at identifying management practices that help maintain or improve soil functions. The sixth and seventh papers evaluate the energy use efficiency and profitability of alternative reduced tillage cropping systems. They suggest that the adoption of alternative soil management practices is largely governed by profitability considerations, which in turn, are likely to be influenced by both energy costs and government programs.

The soil quality studies used existing long-term cropping system experiments with well-defined treatment histories. Many of these long-term experiments were established by

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scientists who documented the detrimental effects of fallow on the soil resource and developed the more intensive cropping systems now common in the Great Plains. These experiments were designed to reduce the incidence of fallow, introduce crop rotations to break weed and disease cycles, and reduce tillage to maintain crop residue as a protective layer on the soil surface. These well-managed long-term studies provided the type of data needed to evaluate rigorously a number of recently developed analytical methods and assessment tools. The goal of the study reported in this series of papers is to identify soil properties that influence important soil functions, and evaluate accessible methods for measuring those properties. Many of the measured properties were used to evaluate two recently developed assessment tools. The soil properties identified, the methods validated, and the assessment tools tested will be useful for comparing future developments in soil management practices.

This series of papers also provides some important perspectives on how the timing and method of soil sampling can influence the interrelation of soil quality information. Careful documentation of sampling depth and measurement of bulk density is essential for understanding the temporal dynamics exhibited by many soil properties. It is only after the temporal dynamics are understood that management effects can be assessed.

Conditions in agriculture have changed a great deal since cropping began in the Great Plains. Crop–fallow was practiced for several decades with the dominant crop being wheat. As more intensive cropping systems were developed, additional crops were grown in rotation to break weed and disease cycles. Today, farmers readily alter their cropping practices in response to weather patterns, market pressures, and development of new technologies. Since many soil properties respond slowly to changes in management practices, it will be difficult to assess changes in these soil properties in a dynamic management system. It is hoped that the efforts reported in this special issue will contribute toward identifying methods and assessment tools useful for evaluating the sustainability of management systems as they evolve in the future. The review of the book *Managing Soil Quality – Challenges in Modern Agriculture* is a fitting conclusion for this special issue and stresses the importance of management-based thresholds as tools for soil protection, physical and biological integrity, and managing soil quality.

The relationship between energy costs, enterprise profitability and adoption of soil quality-building cropping practices discussed in this issue reminds us of the need to integrate environmental costs and values of ecological services[6] into future research on soil quality impacts, energy use and profitability of alternative cropping systems.

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Great Plains cropping system studies for soil quality assessment

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Abstract

Interactions between environmental conditions and management practices can significantly affect soil function. Soil quality assessments may improve our understanding of how soils interact with the hydrosphere and atmosphere. This information can then be used to develop management practices that improve the capacity of the soil to perform its various functions and help identify physical, chemical, and biological soil attributes to quantify the present state of a soil and detect changes resulting from management. In protocols established by the Great Plains cropping system network, sampling and testing procedures were selected to identify physical, chemical, and biological soil attributes responsive to management that may serve as useful indicators in assessing the effects of management on the soil resource. Eight existing long-term studies from throughout the Great Plains in the central USA were used to make these assessments because, (1) many years are required for certain soil properties to change measurably; (2) annual weather causes variation in system performance; and (3) the soil pools of interest are spatially variable. This paper includes detailed descriptions of the treatments and sites, and both long-term and short-term (1999–2002) data on precipitation, temperature, and yields for each location.

Key words: crop rotation, tillage, no-tillage, conventional management, alternative management, soil resource

Introduction

Soils serve a multitude of functions and play important roles in environmental quality through interactions with the hydrosphere and the atmosphere. Management of the soil resource affects how efficiently the soil performs its various functions and ultimately impacts agronomic productivity and environmental quality. There is currently a great deal of interest in improving our understanding of how soils interact with the hydrosphere and atmosphere, in developing management practices that improve the capacity of the soil to perform its various functions, and in identifying physical, chemical, and biological soil attributes that can be used to quantify the present state of the soil and detect changes in the state of the soil resulting from management.

A workshop held in 1999 identified soil quality as a major research issue. Specifically, emphasis was put on research that provides baseline information about the present status of soils, that determines how management practices affect soils, and that develops useful indicators for assessing the current status and detecting changes resulting from management.

A number of physical, chemical, and biological soil attributes have been proposed for use in assessing soil quality. Several lists of attributes have been suggested for comprising a minimum data set and combinations of attributes have been incorporated into indices having potential for assessing soil function and management impacts[1–4]. Many studies have compared various soil quality attributes under different management systems

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[e.g., comparing crop–fallow to annual cropping, conventional (CON) tillage to conservation tillage, or CON farming to organic farming]. Generally these studies have made inferences about management practices based on the differences in soil properties measured after the soils have been under the management treatments of interest for some time. Such studies can create data sets that quantify differences in various soil attributes due to different management systems, define the expected range and mean values for various soil attributes, and improve our understanding of management effects on the soil resource.

In spite of the number of studies conducted in this area, our understanding of the temporal variation exhibited by various soil attributes is relatively poor. Improving our understanding of the temporal dynamics will aid in designing sampling strategies (e.g., what is the optimum time during the year to assess management effects?) and assist in interpreting results. Separating temporal dynamics from responses to management will help in identifying attributes useful for assessing the effect of management practices on the soil resource.

Long-term studies that continue for at least a decade are usually required to detect management effects on the soil resource. Many years are required to average out the effect of annual weather variation and because it takes time for gradual changes to reach a magnitude detectable against spatially variable large background. Many variables can be fractioned into components (e.g., mineral soil into particle size fractions or aggregate size and stability fractions; organic C into particulate organic matter, microbial biomass C, etc.; and infiltration among tensions or pore sizes) varying in response to management. Identification of components more responsive to management than the variable as a whole would allow more rapid assessment of management effects on the soil resource.

Given the spatial variability exhibited by soil organic matter, the wide variety of soils, and the diverse management practices involved, computer models will be needed for assessing management scenarios and predicting future trends in soil properties. Long-term data are needed for validation of potential models to provide confidence in decisions based on simulation results.

The objective of this paper is to provide background information on the eight long-term cropping system studies in a Great Plains regional project, the results of which are reported in the accompanying papers. For each of the studies, this paper describes site characteristics (including weather data), management practices of the original objectives, and major findings. Within each study, the regional project selected two cropping system treatments to represent CON and alternative (ALT) practices. This paper describes those specific systems and the crop they produced.

Study Sites

Soil quality assessments were done at eight locations spanning north to south gradients in both mean annual temperature (3.6–10.5°C) and east to west gradients in annual precipitation (34.5–76.6 cm) in the Great Plains region. The eight locations are: Akron, Colorado (CO); Brookings, South Dakota (SD); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan, ND; Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada. At each location, long-term experiments compared various unirrigated management systems representative of the currently predominant practices as well as ALT practices having potential for that area. A preliminary static soil quality assessment concluded that differences in soil quality existed between contrasting management practices at several of these locations[5].

Akron, CO: no-till crop rotations to replace fallow and increase performance

In 1990, the ALT crop rotation study was established at the USDA Central Great Plains Research Station to compare the predominant wheat–fallow rotation to ALT crop rotations that minimize or eliminate fallow periods[6]. Of the 23 rotations in this study, CON tillage winter wheat (*Tritium aestivum* L.)–fallow was selected as the CON treatment and no-tillage winter wheat–corn (*Zea mays* L.)–proso millet (*Panicum miliaceum* L.) as the ALT treatment (Table 1). The experiment on a Weld silt loam (fine, smectitic, mesic, Aridic Argiustolls) uses a randomized complete block design with three replications. In the CON system, wheat was planted in September–October and harvested the subsequent July. The land is then fallowed for 14 months and weeds are controlled with V-blade sweeps (3–6 operations per year depending on weather). In the ALT system, corn, millet, and wheat are seeded no-till directly into the previous crop's undisturbed stubble. Weeds are controlled with contact herbicides at recommended rates between crops, and both residual and contact herbicides are used for in-season weed control in corn and millet. Grain yields are reported at 13.5% moisture for millet and wheat and 15.5% moisture for corn. All phases of each rotation appear each year as individual experimental plots of 9.1 m × 30.5 m in size. Additional details of the plot area, tillage systems, and experimental design are given in Anderson et al.[6] and details of the soil characteristics are provided in Bowman et al.[7] Eliminating fallow using the ALT system gave mean annual yields double those of wheat–fallow[6] and increased gross returns[6].

Brookings, SD: ALT crop rotations and reduced purchased N inputs

In 1990, a cropping rotation–N-fertilization rate experiment was established at the Eastern South Dakota Soil and Water Research Farm near Brookings, SD. The objective of the study was to understand the interactions of soils, tillage intensity, crop rotation, and agricultural chemical inputs on crop yield and soil properties[8]. Soil at the site is a Barnes clay loam (fine-loamy, mixed Udic Haploborolls) soil with nearly level topography. This soil is typical of those found

Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings, SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW–WW–SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied = N fertilizer application rate based on soil test results.
[2] Abbreviations: A = alfalfa, C = corn, DW = durum spring wheat, F = summer fallow, L = lentil, M = proso millet, OCL = oat + clover, P = field pea, SB = soybean, SO = sorghum, SU = sunflower, SW = spring wheat, WW = winter wheat.

in eastern South Dakota and western Minnesota and similar to soils common to the northern Corn Belt. Soil tests conducted in the fall of 1989, using the methods of Gelderman et al.[9] revealed 16.5 g kg^{-1} organic matter, extractable concentrations of 14.8 mg kg^{-1} NO_3-N, 9.2 mg kg^{-1} P (Olsen method), and 192 mg kg^{-1} K in the top 26 cm (Ap1 horizon) of the soil profile[10].

The study included three main plot conventionally tilled crop rotations (monoculture, 2-year rotation, and 4-year rotation), each subdivided into three input level subplot treatments. All crops in the rotation treatments were present each year with three replications.

For soil quality assessment, the continuous corn monoculture was selected as the CON treatment and the corn–soybean [*Glycine max* (L.) Merr.]–spring wheat (*Triticum aestivum* L.) under-seeded with alfalfa (*Medicago sativa* L.)–alfalfa 4-year rotation was selected as the ALT treatment (Table 1). Corn and soybean were planted with 76 cm row spacing. Wheat and alfalfa were seeded with a drill. No chemical inputs (fertilizers, herbicides, or insecticides) were applied to the 4-year rotation plots. Corn, soybean, and wheat were harvested at physiological maturity (corn and soybean in late September or early October; wheat in July) for grain and stover yields. Alfalfa was harvested 2 or 3 times per year.

Corn yield responded differently to inputs depending on whether it was grown in rotation with soybean or in monoculture. Corn yields were greater following soybean than in monoculture at an intermediate level of inputs but yields were similar between the two systems at a high level of inputs[8]. Pikul et al.[11] reported that soybean yield increased with starter N fertilizer in 9 of 11 years. Rotation and N fertilization affected N mineralization with highest mineralization rates observed in rotations that included a legume, especially alfalfa, and with a slight decline in mineralization rates with increasing N-fertilization rate[12]. This study has shown that corn yields can be maintained with reduced inputs when the corn is grown in rotation with soybean, soybean yields respond to starter N fertilizer, and many soil properties improved when crops were grown in rotation.

Bushland, TX: conservation tillage and water conservation

A tillage study was established in 1983 on graded-terraced watersheds at the USDA-ARS Conservation and Production Research Laboratory on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) averaging 10 g kg^{-1} (0–15 cm) organic C, medium P and very high K soil test levels. The objective of this study was to compare the water conservation effects of no tillage and stubble-mulch tillage practices in winter wheat–sorghum (*Sorghum bicolor* (L.) Moench)–fallow and continuous wheat cropping systems[13]. For soil quality assessments, a single phase of the wheat–sorghum–fallow rotation was selected as the CON treatment and continuous winter wheat as the ALT treatment, both under no-tillage management (Table 1).

Sorghum was seeded in 0.76-m rows in late May or early June. Winter wheat was seeded in 0.30-m rows using a hoe-press grain drill when adequate moisture was present from late September to early November. Weeds were controlled using a combination of broad-spectrum and pre-plant herbicides. The plots received no fertilizers throughout the duration of the study. Wheat grain and straw were harvested at grain maturity typically in late June or early

July. Sorghum grain and stover were harvested after a killing freeze typically in late October or early November. Jones and Popham[13] provide further details of weed control, experimental layout, and cultural practices for these long-term plots.

Conservation tillage practices result in water conservation allowing more intensive cropping and a reduction in the incidence of fallow in the southern Great Plains. Stubble mulch tillage was found to increase infiltration and reduce runoff losses but the four or five tillage operations needed to control weeds also increased evaporation losses when compared to no-tillage[14]. No-tillage resulted in more plant available water at the end of the fallow period when compared to stubble mulch tillage. Sorghum was found to be well adapted to this region and outyielded wheat. Highest annualized yields were reported for continuous sorghum followed by wheat–sorghum–fallow, continuous wheat, and wheat–fallow[13].

Fargo, ND: no-till versus plow with increased crop diversity and decreased N fertilization

In 1977, a dryland tillage experiment was initiated on 2 hectares located 8 km NW of Fargo, ND on the NW22 research land of the North Dakota Agricultural Experiment Station. The soil is mapped as a Fargo silty clay (fine, smectitic, frigid, Typic Epiaquert) with average soil tests in the 0–15-cm depth of 41 g kg^{-1} organic matter, $pH_{1:1\ water}$ 7.7, 47 kg P ha^{-1} and 629 kg K ha^{-1}. The objective of this study was to determine the effect of tillage intensity on dry matter production and nutrient uptake by crops commonly grown in the Red River Valley[15]. Four primary tillage systems were used after the small grain crop, including fall plow, fall sweep, fall intertill (strip till), and no-till. Each tillage block was replicated four times. A rotation of sugarbeet (*Beta vulgaris* L.), spring wheat, sunflower (*Helianthus annuus* L.), and barley (*Hordeum vulgare* L.) was maintained for the first 8 years. Sugarbeet was replaced by soybean in the rotation during the next 2 years and the sweep system was changed to fall chisel.

In 1987, the rotation was switched to a small grain and grain legume rotation (one crop per year) that included spring wheat, durum (*Triticum turgidum* L.), soybean, drybean (*Phaseolus vulgaris*), and field pea (*Pisum sativum* L.)[16,17]. Tillage systems remained the same except that the intertill system was switched to fall disk in 1998. After the grain legume was harvested, the tillage system was split as before, with one half receiving no tillage and the other half receiving a chisel operation. In the spring of 1997, a nitrogen fertilizer variable was added to the study with 0, 45, 90, and 135 kg N ha^{-1} randomly split across each replication in a split block arrangement.

For soil quality assessment, the CON treatment was a small grain (durum wheat even years)–grain legume (field pea odd years) rotation using plow tillage with no N fertilizer. The ALT treatment was the same, but using no-till management (Table 1). For both treatments, grain and stover dry matter were determined at physiological maturity of each crop (late August to early September).

This study demonstrated that the response to tillage is crop dependent. When soybean is water stressed early in the growing season, early maturing cultivars are adversely affected while late maturing cultivars are not. When water stress occurs, early maturing cultivars yield better under no-tillage, and with no water stress both early and late maturing cultivars have similar yields across tillage practices[15]. Nutrient stratification observed in soils under reduced tillage did not affect dry matter and nutrient content of either soybean[18] or sunflower[20]. Sunflower seed yield and quality were not affected by reduced tillage[19]. During a normal growing season, dry bean yields were greater under no-tillage, while in wet years more intensive tillage improved yields and strip-tillage performed best averaged across all years[16]. Highest plant nutrient contents were observed with plow tillage[21]. This study demonstrated that crop performance in this soil is the result of an interaction of weather during the growing season, tillage, and cultivar.

Mandan, ND: conservation tillage and annual cropping to replace fallow

In 1984, a conservation tillage-cropping system study was established near Mandan, ND, to determine the long-term effects of CON, minimum, and no-tillage residue management systems on water conservation and use, N use, and crop yields. The study was intended to be long-term so that soil C, N, and P cycling could be assessed[22]. The experiment was located about 6 km southwest of Mandan, ND on a Wilton silt loam (fine-silty, mixed, superactive frigid Pachic Haplustoll). The soil pH was 6.4 and organic C concentration was 21.4 g kg^{-1} in the surface 76 mm. The area was previously cropped to sunflower in 1983, to use all available soil water and N to a depth of 1.5 m. In the fall of 1983, 45 kg P ha^{-1} as concentrated superphosphate was broadcast over the entire research area. Sodium bicarbonate extractable P in the surface 152 mm ranged from 20 to 26 mg kg^{-1} in the spring of 1984.

Two crop sequences, three residue managements, three N fertilizer rates, and two crop cultivars were included in the research. Three replicates of crop sequences, residue management, N fertilizer rates, and crop cultivars were arranged in a randomized complete block design. Specific treatments selected for the soil quality assessments were spring wheat–fallow with CON residue management leaving <30% soil surface covered by residue fertilized at a rate of 22 kg N ha^{-1} as the CON treatment, and spring wheat–winter wheat–sunflower with no-tillage residue management leaving >60% soil surface covered by residue and fertilized at a rate of 67 kg N ha^{-1} as the ALT treatment (Table 1).

CON tillage used an undercutter (81-cm sweeps) as needed between crops and a tandem disk once just prior to planting to control weeds. Under no-tillage, weeds were

controlled only by herbicides. Nitrogen fertilizer (ammonium nitrate) was broadcast in late April prior to seeding spring wheat in early May and sunflower in late May. For winter wheat, N fertilizer was applied at the same time as for spring wheat. Winter wheat, spring wheat, and sunflower were harvested at physiological maturity in early August, mid-August, and mid-October, respectively, to determine grain and straw yield. Details on soil characterization and management information are provided by Black and Tanaka[22].

In the wheat–fallow system, yield responses to N fertilization occurred in years where spring soil NO_3-N was low. Cultivars were not consistent in their response to N fertilization or tillage. Slight yield reductions were observed in no-tillage and minimum tillage when compared to CON tillage in some of the years[23]. With annual cropping, grain yields did not respond to tillage or N fertilization when plant available water was <300 mm. When plant available water was 300–400 mm, grain yields were greater with no-tillage than with CON or minimum tillage. When plant available water exceeded 400 mm grain yields were greatest under CON tillage[24].

In the 0–5-cm depth, N-mineralization rates were greater in the fallow phase than in the crop phase of the wheat–fallow system, were greater in the spring wheat phase of the annual cropping system than in the spring wheat phase of the wheat–fallow system, and were greater in the spring wheat and sunflower phase than in the winter wheat phase of the annual cropping system. In the 5–15-cm depth, N-mineralization rates were greater in the annual cropping system than in the wheat–fallow system[25].

As tillage intensity decreased, soil organic C sequestration increased in the annual cropping system. In the annual cropping system, no-tillage resulted in the sequestration of 233 kg C ha^{-1} yr^{-1}, minimum tillage resulted in the sequestration of 25 kg C ha^{-1} yr^{-1}, and CON tillage resulted in the loss of 141 kg C ha^{-1} yr^{-1}. Soil organic C was lost from all tillage treatments in the crop–fallow system. Nitrogen-fertilizer rates did not affect soil organic C[26].

This study demonstrated that conservation tillage and annual cropping could replace crop–fallow. Elimination of crop–fallow and use of conservation tillage resulted in higher annualized grain yields, higher utilization of fertilizer N, improved cycling of N, and sequestration of C in soil organic matter.

Mead, NE: crop rotation for increased SOM levels, and N and precipitation use efficiency

The experiment was established in 1982 on the Agronomy Farm at the University of Nebraska Agricultural Research and Development Center near Mead, NE on a well-drained Sharpsburg silty clay loam (fine, smectitic, mesic Typic Argiudoll). This soil has an average organic matter content of 31 g kg^{-1} and soil test P and K levels in the very high categories in the surface 7.5 cm (according to University of Nebraska Soil Testing Laboratory NebGuides). The original objective of the study was to determine the long-term effects of crop rotation and N fertilization on several crop and soil parameters.

Seven cropping systems (three monoculture, two 2-year, and two 4-year rotations) with three rates of N fertilizer were included in the study. Each phase of every rotation occurred every year for a total of 15 rotational treatments. Treatments were assigned to experimental units in factorial combinations of rotation and crop within rotation in five randomized complete blocks.

For soil quality assessments, the high N-rate subplot treatment for both the continuous corn (CON treatment) and the 4-year soybean–sorghum–oat [*Avena sativa* (L.)] + clover (80% yellow sweetclover [*Melilotus officinalis* (L.) Lam.] + 20% red clover [*Trifolium pratense*])–corn system (ALT treatment) were selected (Table 1). Nitrogen applications of 180 kg N ha^{-1} for corn and sorghum and 68 kg N ha^{-1} for soybean and oat + clover as they appeared in these systems were made in May or early- to mid-June. All plots were tilled once or twice with a tandem disk just prior to planting each year for all crops.

Oat was harvested at physiological maturity, usually in early July to determine grain and stover yields. Corn, soybean, and sorghum were harvested for grain and stover yields at physiological maturity, usually in September or early October.

Results after the first full cycle of the 4-year rotations indicated significant differences in crop responses to rotation. Corn and soybean grain yields were both significantly greater when grown in rotation as compared to monoculture systems, while sorghum yields were the same in rotation and monoculture systems[27–29]. Nitrogen fertilizer efficiency determined by using ^{15}N methods was shown to be greater for corn and sorghum grown in crop rotation systems with legumes than in continuous systems[30,31], while soybean utilized applied N fertilizer similarly in all cropping systems[32]. As a result, crop rotations including legumes were shown to not only require less fertilizer N for optimum yields, but also that residual soil N levels were lower in rotation systems than in the monoculture corn and grain sorghum systems, and also that residual soil N levels following soybean were less than for any of the other crops in the study[33].

Changes in soil C ranged from a small net loss in the monoculture soybean cropping system to a gain of 100–200 kg C ha^{-1} yr^{-1} for cropping systems including monoculture corn and sorghum at optimum N-fertilizer rates and 4-year rotations of corn–soybean–sorghum–oat + clover and corn–oat + clover–sorghum–soybean after 8 years[34]. Compared to monocultures, corn, sorghum, and soybean grown in rotation produced more dry matter per unit of water received, thereby reducing year-to-year variability and resulting in more stable long-term production and economic returns[35,36]. The corn–soybean rotation was significantly less risky than those crops grown in monoculture[37,38].

This study demonstrated that crop rotation generally increases crop yields, improves both N-fertilizer and precipitation use efficiency, reduces soil N available for leaching, increases soil organic matter levels, and results in greater yield stability and economic returns. Monoculture systems generally require greater management inputs and have greater agronomic[39] and economic risk.

Sidney, MT: annual cropping with no-tillage replaces CON crop–fallow

In 1983, a crop rotation experiment was initiated 11 km north of Culbertson, MT on a Dooley sandy loam (fine-loamy, mixed, Typic Argiboroll). The objective of this study was to compare crop and soil effects of CON crop–fallow and non-traditional cropping practices under tilled and no-tillage conditions[40]. Two treatments from a larger rotation experiment were selected for the present study: (i) spring wheat–fallow with CON tillage as the CON treatment, and (ii) continuous spring wheat with no-tillage as the ALT treatment (Table 1). Both phases of the spring wheat–fallow treatment appear each year. The study was laid out in a randomized complete block design with four replications, with a plot size of 30 m × 12 m.

The spring wheat–fallow treatment had no after-harvest tillage, but was disked prior to seeding for seedbed preparation. Depending on soil and weather conditions, fallowing was accomplished by either mechanical or chemical means. Spring wheat was seeded with a double-disk opener drill. All plots except fallow received 56 kg N ha^{-1} (ammonium nitrate) broadcast at time of seeding from 1983–1985. From 1986–1995 the rate was changed to 34 kg N ha^{-1} and it has been 45 kg N ha^{-1} since 1996. Fallow plots received 34 kg N ha^{-1} in every crop year. Long-term P requirements were met by applying and incorporating into the surface 5 cm of soil 560 kg P ha^{-1} $(NH_4)_2HPO_4$ (18-46-0) (N–P–K) prior to the establishment of the study. Wheat grain and straw were harvested at physiological maturity typically in late August or early September.

After 7 years there were no differences in soil P, NO_3-N, and pH for soils between annual cropping and crop–fallow. Bulk density was lower in the surface depth of the no-tillage annual cropping treatment than in the conventionally tilled crop–fallow treatment[40]. Bulk density did not change due to freeze thaw during the winter. Point resistance was 2.2 MPa in the surface layers of conventionally tilled wheat–fallow compared to 1.7 MPa in no-tilled annual cropping. Soil organic C was greater in 0–9-cm depth of the no-tillage annual cropping treatment than in the conventionally tilled crop–fallow treatment. Improved soil physical and chemical conditions in the no-tillage annual cropping treatment resulted in higher infiltration rates in both dry and wet soil[41]. This study demonstrated that, based on yield, water use efficiency, soil organic C, and bulk density, the most efficient crop and soil management system for this region was annual cropping with no-tillage.

Swift Current, SK: crop substitution for fallow enhances soil productivity

In 1967, a crop rotation experiment was initiated at the Semiarid Prairie Agricultural Research Centre of Agriculture and Agri-Food Canada near Swift Current, SK on a Swinton silt loam (fine-loamy, mixed, calcareous, frigid Typic Haplustoll). The objectives of this study were to evaluate the influence of rotation length, summer fallow substitute crops, and N and P fertilizers on crop yields, grain protein, N and P uptake and changes in soil physical, chemical, and biological properties[42]. Two rotations within a larger rotation experiment were selected for soil quality assessment: (i) spring wheat–fallow as the CON treatment and (ii) spring wheat–lentil (*Lens culinaris* L.) (initiated in 1979) as the ALT treatment (Table 1). There are three replicates. Each phase of both rotations was present every year, but only the wheat after lentil and fallow after wheat phase was sampled in 2000 with the succeeding phase (lentil after wheat and wheat after fallow, respectively) being sampled in 2001.

In-crop weed control was achieved with post-emergent herbicides as required. Both rotations received N and P fertilizer as required based on soil nutrients present in October sampling. Crop stubbles were tilled just prior to planting. General seedbed preparation, fertilization, herbicide application, planting, harvesting and tillage practices for this experiment have been reported previously[42].

A large amount of information has been published from this study. Early publications reported agronomic production, crop N utilization, and N distribution in the soil. Wheat yields were found to be inversely related to the frequency of fallow and directly related to rainfall received during the growing season. Grain quality was also evaluated, with wheat grain protein being greatest in wheat after fallow, slightly less for continuous wheat with N fertilizer, and lowest for continuous wheat without N fertilizer. Wheat grain P concentration was directly related to rainfall received during the growing season and was greater for wheat in rotation than for wheat following fallow[42]. Utilization of N by the wheat crop was dependent on rainfall received during the growing season. During dry years, NO_3-N accumulated in the soil and this accumulation was greater for soils receiving N fertilizer. During wet years, the crop utilized NO_3-N and there were no differences between fertilized and unfertilized plots. The accumulation of NO_3-N below the rooting zone resulted in leaching losses and potential contamination of groundwater even under annual cropping[43]. Biederbeck et al.[44] reported that frequent fallow impaired soil biological activity but the trend was reversible with more intense cropping and use of adequate N and P fertilizer.

Twenty-four years after establishment of this rotation study, Campbell and Zentner[45] assessed trends in soil organic matter. They found that variation in organic matter in the 0–15-cm depth was dependent on the amount of crop residue returned to the soil. During drought years, crop

production is reduced and organic matter declined in all rotations. In normal and above normal precipitation years, adequate fertilization and minimization of the use of fallow resulted in maintenance or accrual of soil organic matter. This long-term study has provided a wealth of information regarding crop rotation effects on soil physical, chemical, and biological properties, potential environmental impacts associated with cropping practices, and agronomic and economic performance of these cropping systems.

Opportunity Research

These sites have been used for a number of studies but not within the original objectives. At Akron, Bowman et al.[7] determined that annual cropping increased the soil organic matter by 20% and particulate organic matter by 100%, and soluble organic C by 33% in the 0–5-cm depth when compared to wheat–fallow. However, inclusion of sunflower in a rotation resulted in lower particulate organic matter and total soil organic matter concentrations in the 0–5-cm depth Bowman et al.[46]. Bowman and Halvorson[47] found that P availability increased in the 0–5-cm depth with annual cropping, likely due to increased P recycling in residue and litter in the more intensive systems. Wright and Anderson[48] used soils from treatments differing in cropping intensity to determine that aggregate stability and glomalin (a glycoprotein produced by mycorrhizal fungi) concentration were positively correlated and increased as cropping intensity increased.

At Mandan, Merrill et al.[49] measured changes in aggregate size distribution from fall to spring, quantifying over-winter processes that affect soil susceptibility to wind erosion soil losses. Wind erosion losses from the various tillage treatments were also estimated during a drought cycle[50]. Yield reductions during severe drought were so great that residue levels, even with no-tillage, were insufficient for protecting the soil from wind erosion. The effect of drought on root growth of cereals was also studied by Merrill et al.[51]. Use of a no-tillage system resulted in greater root length growth and depth of rooting in spring wheat when compared to a CON tillage system. This enhanced root growth resulted in greater above-ground growth in 2 of the 3 years. When soil organic C results were combined with a suite of physical, chemical, and biological soil attributes, Wienhold and Halvorson[52] concluded that annual cropping resulted in improved soil quality when compared to crop–fallow and that soil quality improved as tillage intensity decreased. DeVuyst and Halvorson[53] compared economic efficiency among the systems at Mandan and found crop–fallow and CON tillage in an annual cropping system to be less efficient than CON tillage in an annual cropping system. These last two studies demonstrated that CON tillage and annual cropping improved both the soil resource and the producer's income.

CON tillage resulted in the formation of a tillage pan that was thought to reduce wheat yields in eastern Montana. Pikul and Aase[54] utilized the cropping system study at Sidney to determine if subsoiling (paratilling) would fracture the tillage pan and improve water use and yield of wheat. Subsoiling resulted in measurable improvement in cone index, bulk density, infiltration rate, and average water content. During the 3 years of this study, growing season precipitation was sufficient that improvements in water storage resulting from improved soil physical conditions did not translate into increased wheat yields. Long-term soil organic matter dynamics measured in the cropping system study at Swift Current were used to validate the Century model[55].

Weather and Crop Yields

The locations used in this study all experience continental climates, characterized by large variation in temperature and precipitation both within a year and among years. Precipitation and temperature recorded during the 4 years of this study typify the variation experienced in this region. Below average annual precipitation occurred at Akron in 2000 and 2002; at Brookings in 1999; at Bushland during 2000–2002; at Mandan in 2002; at Mead during 2000–2002; at Sidney in 2001; and at Swift Current in 2001. Above average annual precipitation occurred at Akron in 1999; at Brookings in 2000 and 2002; at Bushland in 1999; at Fargo in 1999, 2000, and 2002; at Mandan during 1999–2001; at Sidney in 1999 and 2000; and at Swift Current in 2000 and 2002 (Fig. 1).

For crop performance, variation in precipitation within a year is likely more important than total annual precipitation. For example, in 1999 Akron received nearly 11 cm of precipitation above the normal amount but the extra precipitation was all received in August, after the wheat crop was harvested, and was therefore not available to the crop. Nearly all locations have similar examples of large precipitation amounts received during a thunderstorm, skewing the annual total precipitation amount (Fig. 1). When large amounts of precipitation are received over a short time the potential for runoff losses is great and the precipitation is not available to the crop. Extended periods of below normal precipitation (e.g., spring of 2000 and 2002 at Akron) can result in water stress for the crop. The effect of this stress on yield is dependent on the growth stage of the crop.

With the exception of 2002 at Swift Current, the study period was a time of normal or above average annual temperatures at all locations (Fig. 2). Many of the above average annual temperatures recorded in this study result from warmer than average periods during the winter (e.g., Akron in February and March of 1999). Warmer than average temperatures during winter likely have little effect on crop performance. Warmer than average temperatures during the growing season can negatively effect yields if they are severe enough and occur during a critical growth stage (e.g., head development in wheat and silking in corn).

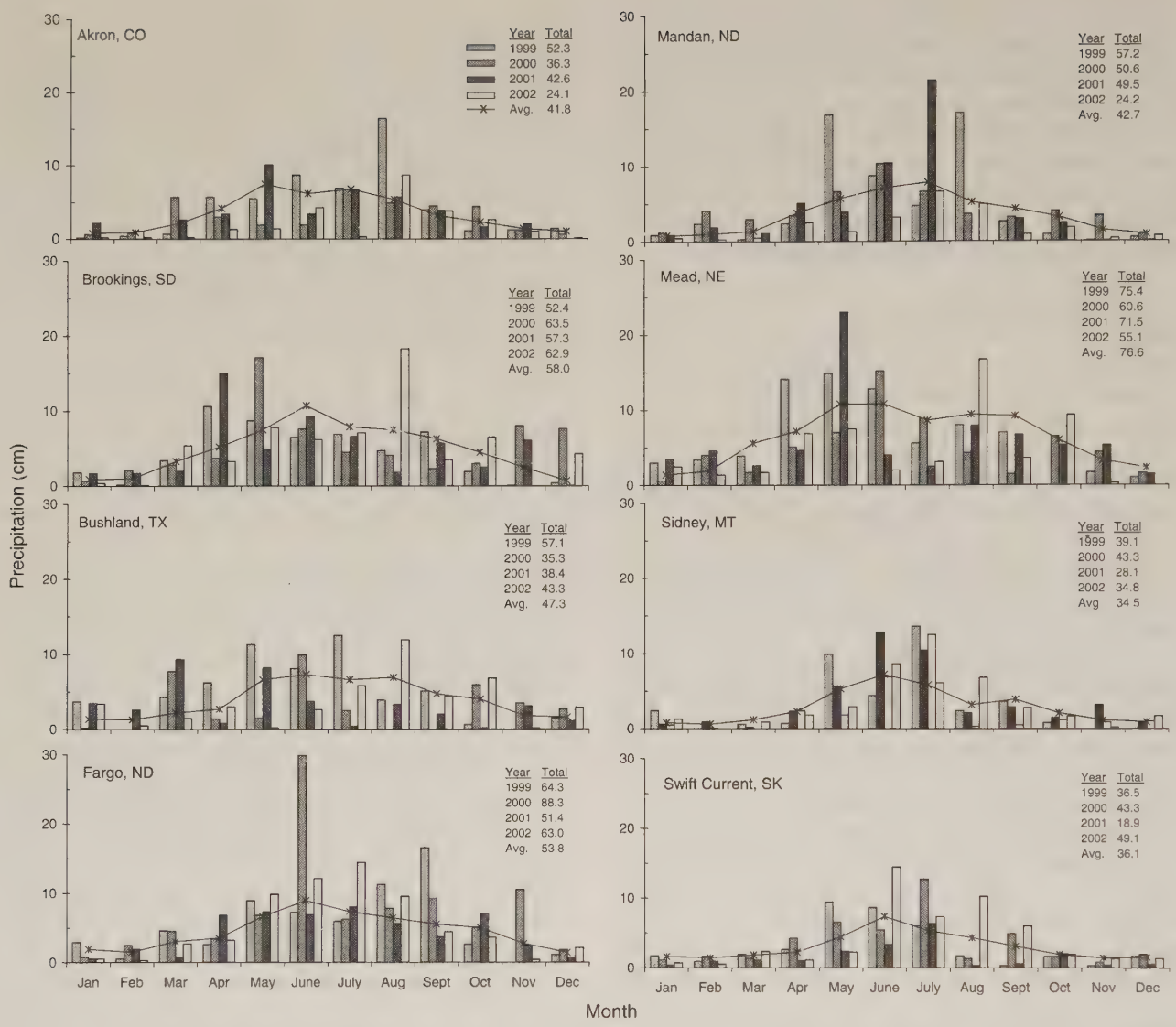

Figure 1. Monthly and yearly precipitation for 1999 through 2002 and long-term averages at each location in the regional soil quality assessment project. Location and number of years for long-term average in parentheses: Akron (93 years), Brookings (30 years), Bushland (64 years), Fargo (30 years), Mandan (30 years), Mead (30 years), Sidney (30 years), and Swift Current (117 years).

Yields for the study period were similar to long-term yields at most sites (Table 2). Higher yields at Fargo are likely due to above average precipitation during the years of the study, while slightly lower yields at Mead are likely due to below average precipitation during the years of the study.

Soil Sampling Protocol

It was planned to sample all soils three times each year from each replicate of each treatment. The actual number of sampling times, however, varied among locations. Some locations had 2- or 3-year rotations and sampling was limited to one complete rotation. Others missed some sampling times due to weather. Due to large differences in the length of the growing season across locations, soil sampling was conducted based on growth stage of the crop. Soil samples were collected prior to planting, midseason [from sorghum plots at stage 6[56] (half bloom), from wheat plots at Haun stage 8[57] (flag leaf), and from corn plots at growth stage VT[58] (tassle)] and after harvest. Samples were collected using a stratified sampling scheme so that within-row and between-row areas of the plot comprised the proper proportion of the composite sample. For small grains with row spacings of 30 cm or less, 50% of the samples were collected from within-row and 50% were collected from between-row areas of the plot. For row crops, 25% of the samples were collected from within-row and 75% of the samples were collected from between-row areas of the plot. In each plot, 15–18 cores were collected to a depth of 30 cm, sectioned into 0–7.5, 7.5–15, and 15–30-cm increments, and composited by depth. A bulk soil sample was collected from the 0–7.5-cm surface increment using a flat blade shovel at five locations within each plot. The

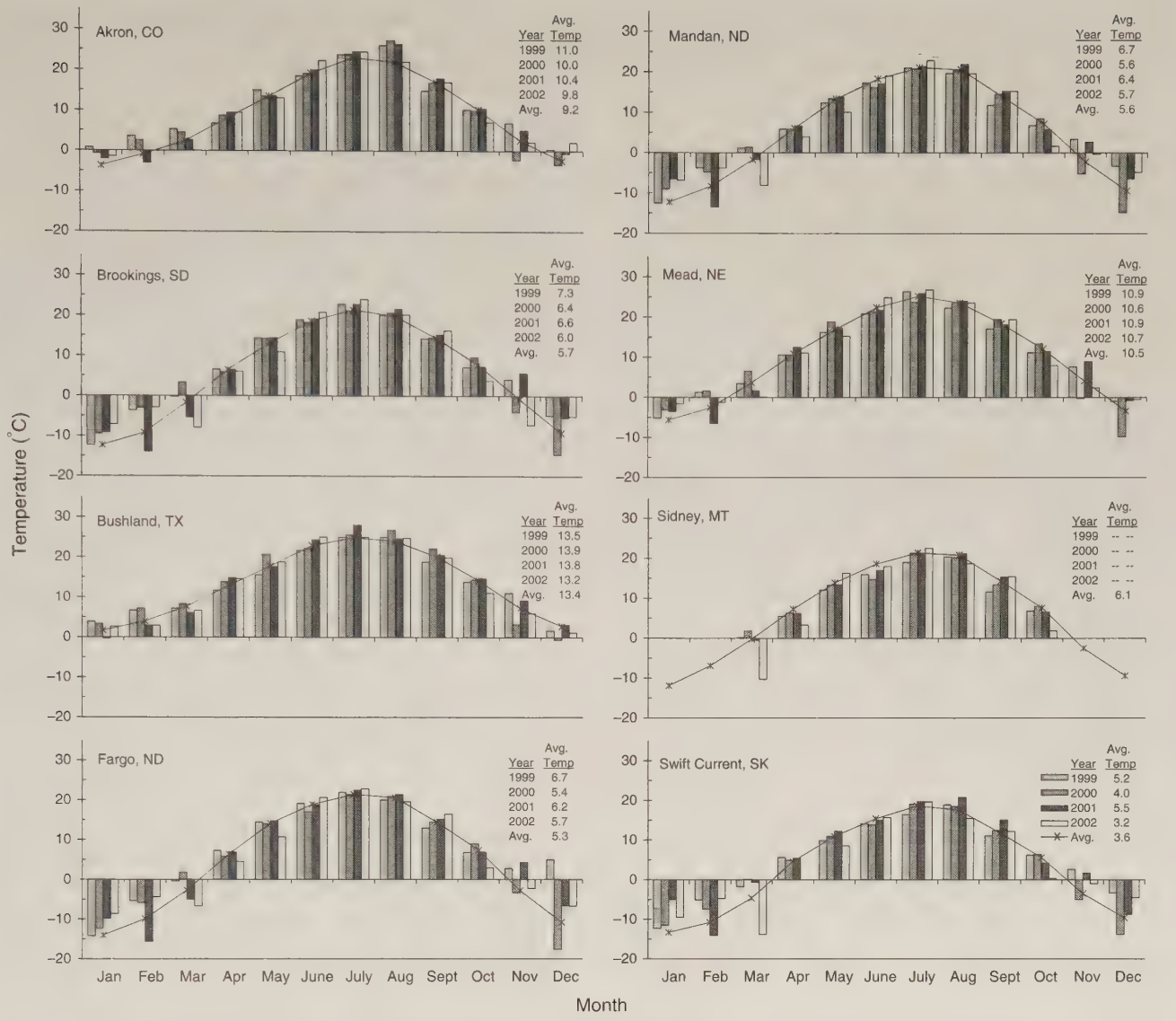

Figure 2. Monthly and yearly average ambient air temperatures for 1999 through 2002 and long-term averages at each location in the regional soil quality assessment project. Location and number of years for long-term average in parentheses: Akron (93 years), Brookings (30 years), Bushland (64 years), Fargo (30 years), Mandan (30 years), Mead (30 years), Sidney (30 years), and Swift Current (117 years).

composite soil sample was stored in plastic bags at 4°C until processed for analysis, and the bulk soil sample was immediately air-dried and stored for further processing.

The mass of the composite soil sample was recorded and a subsample (~20 g) was oven-dried for determination of gravimetric soil water content. The dry mass of the composite sample was then calculated and bulk density determined using the soil probe diameter, number of samples, and depth increment to calculate the volume of soil. A subsample of the field-moist composite soil sample was packaged with ice and sent to the USDA-ARS laboratory in Lincoln, NE for determination of biological soil attributes. The remainder of the composite sample was air-dried. The subsample (~25 g) of the air-dried soil was sent to USDA-ARS laboratory in Morris, MN for fatty acid analysis, a subsample (~50 g) was sent to the USDA-ARS laboratory in Lincoln, NE for determination of loss-on-ignition organic matter and particulate organic matter, and the remaining composite sample was retained at the sampling location for determination of additional soil chemical properties. The bulk soil sample was air-dried and sent to either the USDA-ARS laboratory in Lincoln, NE (Swift Current, SK; Bushland, TX; and Fargo, ND) or Beltsville, MD (Akron, CO; Brookings, SD; Mandan, ND; and Sidney, MT) for determination of aggregate size distribution, aggregate stability, and glomalin concentration. See accompanying papers for descriptions of specific methods[59–61].

Conclusions

Long-term studies such as those described above provide an invaluable resource, on which assessments proposed in this series of papers can be tested both temporally and spatially.

Table 2. Grain and stover dry matter yields each year and long-term (LT) averages for selected conventional and alternative management systems at each location participating in the regional soil quality assessment project.

Location (years of study)	Yield											
	Grain				Mean		Stover				Mean	
	1999	2000	2001	2002	4-year	LT[1]	1999	2000	2001	2002	4-year	LT
	Mg ha^{-1}											
Akron, CO (10)												
WW–F (CT)[2]	2.4	0	3.5	0	1.5	1.1	4.1	–	5.3	–	2.4	2.4
WW–C–M (NT)[2]	1.1	2.4	2.2	0.8	1.4	1.5	2.7	4.8	4.4	1.4	3.3	3.4
Brookings, SD (7)												
Cont. C[2]	5.4	5.5	5.3	4.5	5.2	6.4	5.9	4.7	5.1	4.4	5.0	–
C–SB–SW/Alf-Alf[2]	7.8	2.4	2.6	0	3.2	–	7.5	5.6	–	8.4	–	–
Bushland, TX (20)												
Cont. WW (NT)	1.9	1.5	1.9	0.2	1.4	–	7.2	4.2	3.8	0.3	3.9	–
WW–SG–F (NT)	3.1	2.4	–	0.8	–	–	10.9	3.3	–	3.3	4.4	–
Fargo, ND (15)												
FP–D (Plow)[2]	2.6	2.5	2.5	2.1	2.4	2.1	2.5	5.9	1.8	4.6	3.7	3.5
FP–D (NT)[2]	2.8	2.4	2.4	1.6	2.3	2.0	2.7	5.6	2.3	3.9	3.6	3.5
Mandan, ND (12)												
SW–F (CT)	1.6	–	–	–	1.6	1.1	4.2	–	–	–	4.2	1.8
SW–WW–SF (NT)[2]	1.7	3.2	–	–	2.4	1.7	4.5	–	–	–	4.5	3.4
Mead, NE (20)												
Cont. C	8.8	6.5	6.6	6.0	7.0	7.1	6.9	5.0	6.2	4.3	5.6	6.2
C–SB–SG–OCL[2]	8.9	2.7	4.2	0.7	4.1	4.6	8.8	5.9	7.7	2.2	6.2	5.6
Sidney, MT (13)												
SW–F (CT)	1.0	1.9	1.4	–	1.4	1.2	1.7	–	1.7	–	1.7	1.7
Cont. SW (NT)	1.7	2.7	2.1	–	2.2	1.9	4.4	–	3.7	–	4.1	3.0
Swift Current, SK (23)												
SW–F	–	–	2.3	–	1.5	1.3	–	–	3.2	–	2.5	2.2
Lentil–SW	–	2.4	0.4	–	1.7	1.6	–	4.9	1.5	–	3.3	3.1

[1] Long-term averages for each management system (no. of years in parentheses by location).
[2] Abbreviations: WW = winter wheat, F = fallow, CT = CON till, M = millet, C = corn, NT = no-till, Cont. = continuous, SB = soybean, SW = spring wheat, Alf = alfalfa, FP = field pea, D = durum, SG = sorghum, OCL = oat + clover, SF = sunflower. '–' Indicates missing data or fallow.

Short funding cycles and the requirement for scientists to publish frequently make maintenance of long-term studies difficult[62]. Long time-series are often needed to analyze economic risk and performance[53], evaluate the role of agriculture in C sequestration and global change[63], and determine management effects on soil functions[59–61,64]. The diversity of cropping and tillage system treatments, soils, and climatic conditions in these studies allows inferences from various assessments about long-term effects. These types of studies are required to make determinations about changes in soil properties (especially physical, chemical, and biological) that occur slowly over time, but they also can be used to evaluate short-term effects on crop production. Information from these sites has played a key role in better understanding potential agronomic performance of cropping and soil management systems in this region. In addition, the information has been used to study environmental impacts associated with these systems and the economic implications of shifting from the CON practice to more intensive or diverse systems. These systems also provide information for model validation that allows simulation into the future. Such results should be of value for developing effective policy.

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Cropping system influences on soil physical properties in the Great Plains

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Abstract

Agricultural systems produce both detrimental and beneficial effects on soil quality (SQ). We compared soil physical properties of long-term conventional (CON) and alternative (ALT) cropping systems near Akron, Colorado (CO); Brookings, South Dakota (SD); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan (ND); Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada. Objectives were to quantify the changes in soil physical attributes in cropping systems and assess the potential of individual soil attributes as sensitive indicators of change in SQ. Soil samples were collected three times per year from each treatment at each site for one rotation cycle (4 years at Brookings and Mead). Water infiltration rates were measured. Soil bulk density (BD) and gravimetric water were measured at 0–7.5, 7.5–15, and 15–30 cm depth increments and water-filled pore space ratio (WFPS) was calculated. At six locations, a rotary sieve was used to separate soil (top 5 cm) into six aggregate size groups and calculate mean weight diameter (MWD) of dry aggregates. Under the CON system at Brookings, dry aggregates (>19 mm) abraded into the smallest size class (<0.4 mm) on sieving. In contrast, the large aggregates from the ALT system abraded into size classes between 2 and 6 mm. Dry aggregate size distribution (DASD) shows promise as an indicator of SQ related to susceptibility of soil to wind erosion. Aggregates from CON were least stable in water. Soil C was greater under ALT than CON for both Brookings and Mead. At other locations, MWD of aggregates under continuous crop or no tillage (ALT systems) was greater than MWD under CON. There was no crop system effect on water infiltration rates for locations having the same tillage within cropping system. Tillage resulted in increased, decreased, or unchanged near-surface BD. Because there was significant temporal variation in water infiltration, MWD, and BD, conclusions based on a single point-in-time observation should be avoided. Elevated WFPS at Fargo, Brookings, and Mead may have resulted in anaerobic soil conditions during a portion of the year. Repeated measurements of WFPS or DASD revealed important temporal characteristics of SQ that could be used to judge soil condition as affected by management.

Key words: soil bulk density, dry aggregate stability, rotary sieve, aggregate size distribution, water infiltration rate, water filled pore space, soil organic carbon

Introduction

Considerable research has been conducted on relationships among cropping sequence, soil organic matter (SOM), and various biological and physical soil properties. It is generally accepted that crop production alone has caused a decline in SOM throughout the Great Plains[1,2]. Wheat–fallow crop sequence, being a common agricultural practice, has been implicated as the cause of serious declines in SOM[2–4].

SOM is linked to fertility and desirable soil tilth. Boyle et al.[5], in a review of the influence of SOM on soil aggregation and water infiltration, concluded SOM had a disproportionate effect on soil physical behavior. Hudson[6] reported that soils high in SOM have greater available water-holding capacity than soils of similar texture with less SOM. Bauer and Black[7] found that available water

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capacity remained constant in sandy soils across a range of soil C. However, in medium and fine-textured soil, available water capacity decreased with increasing soil C. Soane[8] reported that soil compaction was sensitive to small changes in SOM and, generally, decreased with increasing SOM. Maintenance of SOM seems to be a key to sustaining the soil resource and crop productivity[9].

The relationship of SOM to soil physical behavior is not always clearly defined. Degens[10] provides a review on the function of labile organic bonding and binding agents related to soil aggregation. Degens[10] suggests that conclusions on soil stabilization resulting from controlled incubation studies contribute little to understanding biological processes under field conditions. Soil organic carbon (SOC) accounted for about 70–90% of the variability in soil aggregate stability of a clay loam soil[11]. Bruce et al.[12] determined that increased phytomass input to a loamy sand increased aggregate stability and water infiltration. On a silt loam, Pikul et al.[13] found a significant correlation of BD and SOC with penetration resistance within the tillage layer. On long-term tillage, residue management, and N-fertility plots, Pikul and Zuzel[14] reported that SOM had a significant effect on porosity of surface crusts. Mulla et al.[15] attempted to quantify differences in aggregate stability between 'conventional (CON)' and 'alternative (ALT)' farms. They were not able to establish a relation between SOM and physical behavior of a Naff silt loam, although surface crusting was observed on the 'CON' but not on the 'ALT' farm.

A clear statement cannot always be made concerning the effect of tillage on runoff and infiltration even though tillage has been shown to affect SOM. Jones et al.[16] found that tillage increased infiltration rates and decreased runoff as compared with no tillage. They attributed these results to surface crusting of no tillage plots. Although tillage decreased runoff, it also increased water erosion of soil. Pikul and Aase[17] found subsoil tillage initially improved water infiltration, but the benefit was short-lived when followed by secondary tillage. Seta et al.[18] found that reduced tillage reduced runoff and sediment loss from 0.01-ha runoff plots subjected to simulated rainfall. At the watershed scale, Edwards et al.[19] could not confidently evaluate the erosion-controlling benefits of no-tillage in a corn–soybean rotation because of great year-to-year variability in measured erosion. Increased water transmission in no-till soil has been attributed to surface-connected macropore channels[20].

Variable relations between tillage and soil BD have also been observed. Investigators have reported greater BD can be expected with no-tillage as compared with CON tillage practices[21–23]. There are reports that tillage has had an insignificant effect on BD[24,25]. Mielke et al.[26] found that fallow tillage did not affect BD in a silt loam soil; however, reduced tillage decreased soil BD in a loam soil. Interpretation of BD measurements can be difficult because large sampling increments may overlap layers of compacted and non-compacted soil and dilute or mask treatment effects. Investigators using thin sampling increments of 0.02 m have successfully identified unique profiles of SOC and BD in long-term tillage and residue management experiments[13,27,28].

The state of the soil physical environment is important for maintaining sustained agronomic production; a concept embodied in the presumption that good soil tilth is a precursor to high crop productivity. Agricultural systems may produce both detrimental and beneficial effects on soil physical condition. Soil compaction frequently occurs when agricultural equipment passes over a field, but little is known about the long-term interaction of crop systems, residue, and fertilizer management on soil physical condition.

A multi-location study was conducted during 1999–2002 at eight Great Plains locations to evaluate a number of physical, chemical, and biological properties associated with SQ. Objectives were to quantify changes in soil physical attributes in cropping systems and assess the potential of individual soil attributes as sensitive indicators of changes in SQ.

Materials and Methods

Contrasting management treatments within eight long-term cropping system studies were compared (Table 1). Treatments selected at each site differed in management intensity, as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity. The Akron, Fargo, and Mandan locations included a tillage variable as well as a cropping intensity and crop species variable in the cropping system. Locations that had the same tillage system but different cropping intensity or crop species in the cropping system were Brookings, Bushland, Mead, Sidney, and Swift Current. Varvel et al.[29] describe these long-term field experiments and standard soil sampling procedure used at each site.

Briefly, soil BD and gravimetric water content (GW)[30] were determined concurrently from core samples taken at 0–7.5, 7.5–15, and 15–30 cm depth increments[31]. Soil samples were collected from the same plots for the duration of one crop rotation cycle. Samples were collected prior to planting, once during the growing season and immediately after harvest. For each depth increment, density and water content relations[32] were used to calculate water-filled pore space ratio (WFPS). Volumetric water (VW) was calculated as:

$$VW = GW \times BD$$

Soil porosity (SP) was calculated as:

$$SP = 1 - BD/2.65$$

where a constant of $2.65\,g\,cm^{-3}$ was used to estimate particle density. WFPS was calculated as:

$$WFPS = VW/SP$$

Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/Soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings, SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW–WW–SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied = N fertilizer application rate based on soil test results.
[2] Abbreviations: A = alfalfa, C = corn, DW = durum spring wheat, F = summer fallow, L = lentil, M = proso millet, OCL = oat + clover, P = field pea, SB = soybean, SO = sorghum, SU = sunflower, SW = spring wheat, WW = winter wheat.

About 7 kg of surface soil (0–5 cm) was randomly (approximately six locations per plot) collected on each plot with a shovel in order to measure dry aggregate size distribution (DASD). Measurements were taken at Brookings and Mead for 3 years, at Bushland, Fargo, and Mandan for 2 years, at Swift Current for only 1 year, and none were taken at Akron and Sidney. After air drying, aggregate size distribution was determined by using a rotary sieve[33]. Mean weight diameters (MWDs)[34] were calculated based on the mass fraction of dry aggregates in six size groups. Group 1 was soil < 0.4 mm, group 2 was 0.4–0.8 mm, group 3 was 0.8–2 mm, group 4 was 2–6 mm, group 5 was 6–19 mm, and group 6 was >19 mm. Representative particle diameter for groups 2–5 was the arithmetic mean of upper and lower sieve diameters, 0.4 mm diameter for group 1, and 19 mm for group 6.

Soil aggregates obtained using the rotary sieve from the Brookings and Mead sites were further processed to measure dry aggregate stability, water stability, and SOC. The rotary sieve tends to abrade aggregates and a measure of this abrasion was determined by running individual aggregate groups through the sieve a second time. The second run provides an estimate of dry aggregate stability and is closely related to susceptibility of the soil to wind erosion[35]. Water stability was measured using a wet sieving device[36]. We measured water stability of dry aggregates to evaluate treatment effect on soil slaking. Soil organic C was determined by combustion using a LECO CN 2000 analyzer (LECO Corp., St Joseph, MI, USA).

Infiltration was measured at six locations on each plot using a single ring infiltrometer[36]. An aluminum infiltration ring, 15 cm diameter by 13 cm long, was inserted into the soil to a depth of 7.5 cm. A piece of plastic wrap was inserted into the ring with the edges of the plastic draping over the edges of the infiltration ring. Distilled water was added to the ring to correspond to a 25 mm depth in the ring. The plastic wrap was removed from the ring and the time required for the water to infiltrate into the soil was measured. After infiltration of the first 25 mm of water, a second volume of water (wet run) was added to the ring to correspond to a 25 mm depth in the ring. The purpose of the first volume of water was to remove the confounding effects of having different antecedent soil water contents at the time of each infiltration test. The time required for the second volume of water to infiltrate was measured and those measurements are reported here. Duplicate infiltration measurements were made within the row (for row crop systems), on trafficked interrow, and non-trafficked interrow.

Analysis of variance was applied to each soil property measured, to determine differences between treatments and sampling times within each location. Analysis of variance and statistical comparisons were completed using the PROC MIXED procedure of SAS[37] assuming a completely randomized block design at each location. Cropping system (treatment) and sampling time were designated as fixed effects and plot replicates nested within treatment was designated as a random effect. Probabilities of WFPS exceeding a critical soil-aeration-threshold (SAT) value were determined using parametric distribution analysis (MINITAB Statistical Software, State College, PA, USA).

Results and Discussion

Infiltration

Cropping system had a significant effect on infiltration for at least one position (Table 2) at the Akron, Fargo, and Mandan locations. All sites except Sidney had a significant time effect on infiltration. Measurements at the Sidney site were only in the row position so that possible differences induced by cropping system may have been negated by the planting operation.

Infiltration rates varied considerably among locations (Table 3). Rates varied from about 1 cm h^{-1} at the Akron and Mandan locations for the track position to over 100 cm h^{-1} at the Fargo location. Generally the track position had lower infiltration rates as compared to the no track or row positions.

A system-by-time interaction was significant at the Akron, Fargo, and Mandan locations, indicating that cropping system effects were not consistent throughout the duration of the experiment. At the Akron location, the CON system had a greater infiltration for the second sampling in 2000 at the no track position, but did not have a significant effect at any other time or position. At the Fargo location, the CON system had greater infiltration at the row and no track positions for the second sampling in 2000 but not at other times. At the Mandan location, there appeared to be a cyclic pattern to the infiltration rate for the ALT system where infiltration rate increased during the growing season and then decreased. The cyclic pattern was less pronounced under the CON system (data not shown).

The significant time effect on infiltration rate at the Brookings location exhibited a cyclic pattern through the growing season. For the no track position, infiltration rate increased during the year. At the row position and tracked position, infiltration rate was lowest at first sampling of the year, increased at the time of the second sampling, then decreased again. A similar, but less pronounced pattern occurred at the Mead location. For the Mead location, infiltration rate in the no track position was lowest at the first sampling of the year, then increased for the second sampling, and then decreased for the third sampling. Infiltration rate for the row and track positions increased during the growing season. At the Swift Current location, there was a general increasing infiltration rate during the course of each year (data not shown).

Table 2. Cropping system (CS) and time (T) effects on infiltration. Locations identified in bold type used the same tillage in the cropping system (other than no till).

Location	Position	CS	T	CS × T
Akron, CO	No track	*[1]	*	*
	Track	NS	*	NS
Brookings, SD	Row	NS	*	NS
	No track	NS	*	NS
	Track	NS	*	NS
Fargo, ND	Row	*	*	*
	No track	NS	*	NS
	Track	NS	NS	NS
Mandan, ND	Row	NS	NS	NS
	No track	*	*	*
Mead, NE	Row	NS	*	NS
	No track	NS	NS	NS
	Track	NS	*	NS
Sidney, MT	Row	NS	NS	NS
Swift Current, SK	No track	NS	NS	NS
	Track	NS	*	NS

[1] Significant treatment effects at $P = 0.05$ shown as * and NS indicates not significant.

Bulk density and water-filled pore space

Mean BD at each of the eight locations ranged from 0.9 g cm^{-3} for the surface depth increment (0–7.5 cm) on

Table 3. Infiltration rates (means of all dates) at each site and field-measurement position.

Location	Position	System	Mean	SD
			..... cm h^{-1}	
Akron, CO	No track	CON	17.9	2.6
		ALT	2.5	2.6
	Track	CON	1.6	0.3
		ALT	1.2	0.3
Brookings, SD	Row	CON	27.4	3.1
		ALT	19.9	3.1
	No track	CON	4.0	1.1
		ALT	2.6	1.1
	Track	CON	16.1	4.0
		ALT	15.0	4.0
Fargo, ND	Row	CON	110.0	15.6
		ALT	31.0	15.6
	No track	CON	129.0	36.4
		ALT	45.9	36.4
	Track	CON	26.3	10.9
		ALT	2.8	10.9
Mandan, ND	Row	CON	NE	NE
		ALT	NE	NE
	No track	CON	1.0	0.6
		ALT	5.0	0.6
	Track	CON	1.9	1.0
		ALT	3.9	1.0
Mead, NE	Row	CON	38.5	16.5
		ALT	77.3	16.7
	No track	CON	NE	NE
		ALT	NE	NE
	Track	CON	20.1	12.0
		ALT	28.1	11.4
Sidney, MT	Row	CON	16.1	3.8
		ALT	14.2	3.8
Swift Current, SK	No track	CON	10.8	3.1
		ALT	3.9	3.1
	Track	CON	4.2	1.1
		ALT	4.6	1.1

NE, the least square means of infiltration rate could not be estimated due to missing values.

native grassland to 1.6 g cm^{-3} for the lower depth increment (loam to sandy clay loam textures) at two locations. Typically, BD was greatest for cropped land as compared with native grassland (Table 4, grassland not shown). The greatest source of variation in BD was attributable to the time (T) of sampling (Table 5).

In tilled plots, there was a tendency for BD in the surface depth increment (0–7.5 cm) to increase during the growing season, probably as a result of soil reconsolidation after spring tillage operations. The tendency for soil reconsolidation is illustrated in Figure 1 for the Brookings site, where surface BD increased during the growing season and subsequently decreased at the beginning of the season except for the end of 2001 and in 2002 when tillage was suspended to permit the growth of alfalfa. Most changes in BD with time probably represent seasonal and annual variations generated by phases in the rotation, tillage and subsequent reconsolidation, and wetting–drying histories. For all locations, measured BD did not exhibit any obvious trend with GW (typical of soils having a low coefficient of linear extensibility). Moreover, there was no observable pattern in the error with which BD was estimated at each sampling time. Hence, we cannot recommend a single crop phase or time of the year at which BD should be measured to obtain the most reliable data for SQ assessments.

Differences in BD between cropping systems were most frequently observed at the soil surface depth increment (Table 5, five locations). For locations in which no-tillage was compared with CON tillage, tillage resulted in increased (Mandan), decreased (Fargo), or unchanged (Akron) BD near the surface. Soil texture and the time of tillage relative to sampling probably influenced how and the degree to which tillage influenced BD. Some BD in the lower depth increment of 15–30 cm approached threshold

Table 4. Dry aggregate size distribution (means of all dates) expressed as mean weight diameter (MWD) of surface soil (top 50 mm) and bulk density (BD) (0–75 mm and 75–150 mm) for conventional (CON) and alternative (ALT) cropping systems. Locations identified in bold type used the same tillage in the cropping system (other than no till).

	MWD		BD			
	Surface soil		0–75 mm		75–150 mm	
	CON	ALT	CON	ALT	CON	ALT
	mm		mg m^{-3}			
Akron			1.27	1.30	1.36	1.38
Brookings	8.32	8.41	1.36	1.35	1.54	1.54
Bushland	8.95	10.85	1.31	1.22	1.43	1.48
Fargo	8.04	10.63	1.00	1.17	1.12	1.22
Mandan	3.99	4.75	1.33	1.14	1.37	1.29
Mead	4.98	5.03	1.17	1.15	1.42	1.39
Sidney	NM	NM	1.44	1.51	1.54	1.52
Swift Current	21.86	22.69	1.23	1.23	1.38	1.42

NM, not measured.

Table 5. Analysis of variance dry aggregate size distribution expressed as mean weight diameter of surface soil (top 50 mm) and bulk density at 0–75 mm and 75–150 mm depths. Locations identified in bold-italic type used the same tillage in the cropping system (other than no till).

Effect	Akron	*Brookings*	Bushland	Fargo	Mandan	*Mead*	Sidney	*Swift Current*
	P-value, MWD of surface soil							
CS	NM	NS	0.051	0.016	NS	NS	NM	NS
T	NM	< 0.001	< 0.001	< 0.001	0.004	< 0.001	NM	0.001
CS × T	NM	0.056	0.083	NS	NS	< 0.001	NM	NS
	P-value, BD (0–75 mm)							
CS	NS	NS	0.014	0.005	0.004	0.018	0.012	NS
T	NS	< 0.001	< 0.001	NS	NS	< 0.001	0.013	NS
CS × T	NS	NS	0.039	NS	NS	NS	NS	NS
	P-value, BD (75–150 mm)							
CS	NS	NS	NS	NS	0.011	0.004	NS	NS
T	< 0.001	< 0.001	< 0.001	0.033	0.008	< 0.001	< 0.001	NS
CS × T	NS	NS	NS	NS	NS	NS	NS	NS

NM = not measured, T = time, significant treatment effects at $P = 0.05$, NS = not significant.

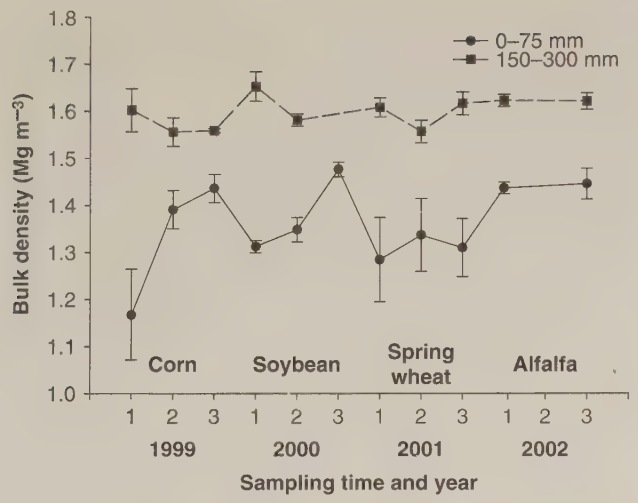

Figure 1. Bulk density throughout four seasons for the corn–soybean–spring wheat–alfalfa rotation (ALT) in Brookings, SD. Error bars represent ±1 SE.

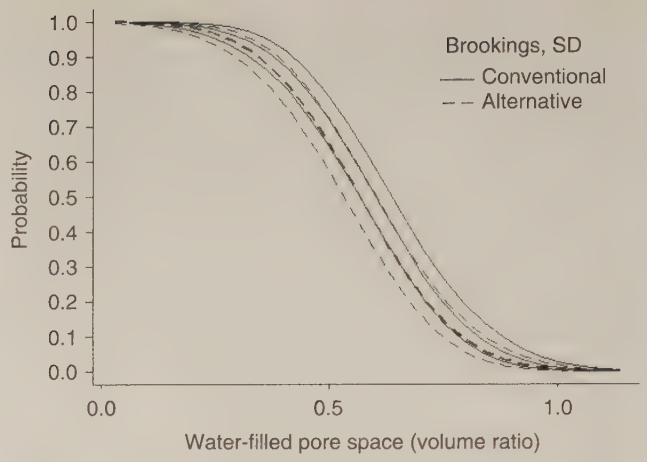

Figure 2. Normal probability function (and 95% confidence interval) of soil having a given volume ratio of water-filled pores (WFPS) within the top 300 mm at any time during the growing season of conventional (CON) and alternative (ALT) rotations at Brookings, SD. There was a 50% probability of achieving a WFPS of 0.6 under CON rotation and a 42% probability under ALT rotation.

densities restrictive to root growth[38]. For example, at Brookings, Mead, and Sidney, the average (cropping systems and dates) BD at 15–30 cm (data not shown) were 1.60, 1.44, and 1.56 g cm^{-3}.

Water-filled porosity, a function of BD and GW, fluctuated during the season and different rotational phases (data not shown). The greatest source of variation in these measurements was attributable to the time of sampling. Cropping systems containing a summer fallow period tended to have greater WFPS and GWs in the lower depth increments as compared to continuously cropped systems with similar tillage operations (Bushland and Swift Current). Comparisons between no tillage and conventionally tilled systems yielded mixed results (Mandan and Fargo).

We used a WFPS ratio of 0.6 as a SAT value[39] to delineate between water limiting and aeration limiting soil microbial processes. Doran et al.[40] have shown that aerobic microbial activity increases to a maximum at 0.6 and then decreases at higher values as aeration becomes limiting. Brookings, Fargo, and Mead had the highest occurrence (with time, treatment, or depth) of having WFPS values $\geqslant$0.6 (there were 198, 117, and 225 measurements of WFPS taken during the study at Brookings, Fargo, and Mead, respectively).

Functions showing the probability of exceeding critical WFPS (with time, treatment, or depth) for Brookings and Fargo are shown in Figures 2 and 3, respectively. At Brookings, probability functions for CON and ALT management were not significantly (95% confidence interval) different. However, there was a 50% probability of exceeding SAT under CON management and a 42% probability of exceeding SAT under ALT management (Fig. 2). Management had a significant (95% confidence interval) effect on WFPS at Fargo (Fig. 3). There was a 58% probability of exceeding SAT under CON

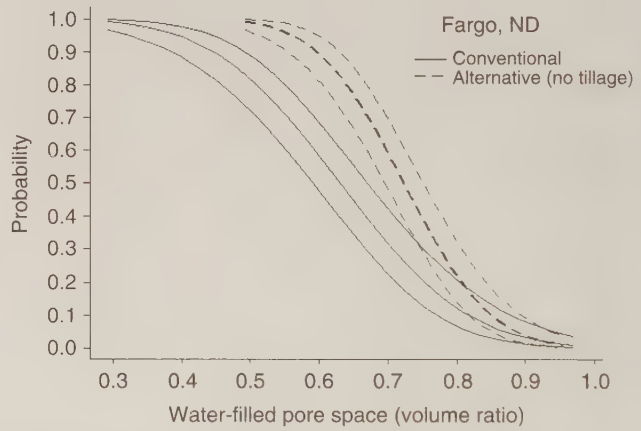

Figure 3. Normal probability function (and 95% confidence interval) of soil having a given volume ratio of water-filled pores (WFPS) within the top 300 mm at any time during the growing season of conventional (CON) and alternative (ALT) rotations at Fargo, ND. There was a 58% probability of achieving a WFPS of 0.6 under CON rotation and a 89% probability under ALT (no tillage) rotation.

management and an 89% probability of exceeding SAT under ALT management.

No tillage was the ALT management at Fargo, and under 'cool and wet' soil conditions there was a greater probability of exceeding SAT under ALT, compared with CON management. At individual sites, precipitation history was the same for both ALT and CON, thus the comparison of WFPS between treatments reflects on only management. Therefore, the differences in soil water content between ALT and CON are a consequence of accelerated soil drying often associated with tillage operations.

Soil aggregates

Cropping system significantly affected MWD at Fargo and Bushland (Tables 4 and 5). Cropping systems at Fargo have a tillage variable where no tillage in the ALT treatment was compared with fall plow tillage in the CON treatment. Both systems at Bushland are under no tillage. MWD was greater under the ALT system at both Bushland and Fargo. Average (all dates) MWD at Bushland was 10.85 mm under ALT and 8.95 mm under CON (Table 4). Soil Microbial biomass C and N at Bushland was greatest under continuous wheat (ALT plots, 331 kg ha^{-1}) compared with a wheat–sorghum–fallow (CON plots, 209 kg ha^{-1}) rotation. This agrees with Liebig et al.[41] who found greater levels of glomalin, and wet aggregate stability under ALT management at Bushland. Mycorrhizal fungi are the source of glomalin and can improve soil structure (as suggested by greater wet aggregate stability and MWD under ALT management compared with CON) by forming water-stable soil aggregates[42].

A large MWD represents a DASD having a large portion of large aggregates. Data suggest that soil aggregates formed under no tillage (a system having elevated organic C) resist disintegration compared with aggregates under tillage. Studies at Brookings of a no tillage and CON tillage corn–soybean rotation (J.L. Pikul, unpublished data 2003) support the observation that dry aggregate stability is greater under no tillage compared with CON tillage. Bisal and Ferguson[43] showed that finer textured soils undergo tremendous changes with time over a multi-year weather cycle. Merrill et al.[44] found that the geometric mean diameter of aggregates on a silt loam soil increased from about 1–2 mm to about 20–30 mm with time. Average MWD for the Swift Current site (Table 4) was similar to that reported by Merrill et al.[44]

There was a significant effect of time on MWD at all locations (Table 5). At Brookings, MWD under ALT (4-year rotation) was significantly greater than CON (continuous corn) in the 4th year of the rotation (alfalfa phase). A similar comparison at Mead showed a smaller MWD under ALT compared with CON. MWD throughout three seasons are shown in Figure 4 for Brookings, SD and Figure 5 for Mead, NE. With the exception of the final measurements in 2002, there was not a statistically significant difference between treatments in MWD for either Brookings or Mead. The crop ending the 4-year rotation at Brookings is alfalfa and the improvement in aggregate stability (represented by a larger MWD value for ALT) may be a consequence of having a perennial like alfalfa in rotation.

MWD is a convenient way to generalize DASD, but expressing a distribution as a single number (e.g., MWD) fails to show differences in properties that influence aggregate stability. Chepil[33] proposed that dry aggregate stability could be measured by multiple passes through a rotary sieve, and we followed those ideas proposed by Chepil. We found differences in the distribution and stability of dry aggregates between treatments at Brookings and, to a lesser extent, treatments at Mead (Table 6).

Erodible fraction is defined as the percentage of soil mass < 0.84 mm diameter, and this parameter has been related to soil wind erodibility. Merrill et al.[44] have shown that the erodible fraction was more sensitive to soil management effects than indices describing aggregate size distribution (e.g., MWD). The ALT treatment at Brookings had significantly greater fraction of large aggregates in groups 5 and 6 (Table 6) following the first sieving than did the CON treatment. As shown by the change in mass on second sieving, aggregates under ALT also had less tendency to abrade into small aggregates (groups 1 and 2) when

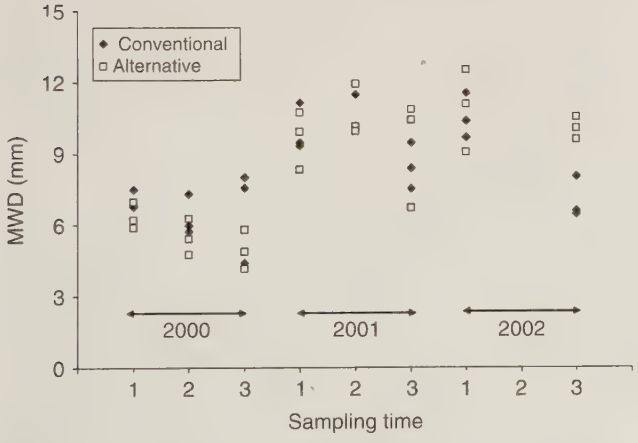

Figure 4. The time course of dry aggregate stability expressed as mean weight diameter (MWD) throughout three seasons for the conventional (CON) and alternative (ALT) rotations at Brookings, SD. In each year, soils were sampled prior to planting, at peak crop biomass, and after harvest. MWD based on aggregate fractions following second sieving.

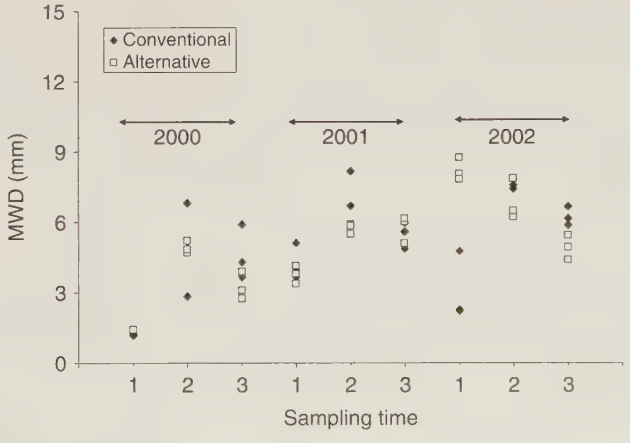

Figure 5. The time course of dry aggregate stability expressed as mean weight diameter (MWD) throughout three seasons for the conventional (CON) and alternative (ALT) rotations at Mead, NE. In each year, soils were sampled prior to planting, at peak crop biomass, and after harvest. MWD based on aggregate fractions following second sieving.

Table 6. Selected properties of soil aggregates for conventional (CON) and alternative (ALT) treatments at the Brookings and Mead sites. DASD, change in mass following second sieving (estimates dry aggregate stability), soil organic C, and water stability were measured on soil collected from the top 50 mm following harvest in 2002. A negative value indicates loss of soil (by abrasion) from that group. Group 1 was soil < 0.4 mm, group 2 was 0.4–0.8 mm, group 3 was 0.8–2 mm, group 4 was 2–6 mm, group 5 was 6–19 mm, and group 6 was >19 mm.

	Aggregate group					
	1	2	3	4	5	6
Brookings						
DASD following 1st sieving ($g\,g^{-1}$)						
CON	0.20	0.10	0.12	0.15	0.20	0.23
ALT	0.07	0.05	0.10	0.16	0.23	0.39
P-value	0.004	0.003	0.055	NS	0.092	0.007
Change in mass following 2nd sieving ($g\,kg^{-1}$)						
CON	36.08	19.60	−0.27	−3.57	−14.80	−38.54
ALT	22.70	15.57	13.67	10.70	14.37	−78.22
P-value	0.040	NS	0.100	0.004	0.016	0.004
Soil organic C ($g\,kg^{-1}$)						
CON	16.23	18.92	18.81	19.33	17.68	18.49
ALT	16.99	20.49	22.53	20.35	17.76	17.71
P-value	NS	NS	0.033	NS	NS	NS
Water stability of dry aggregates (%)						
CON	NM	5.3	19.6	18.3	33.8	NM
ALT	NM	4.0	19.0	32.7	40.2	NM
P-value		NS	NS	0.099	NS	
Mead						
DASD following 1st sieving ($g\,g^{-1}$)						
CON	0.16	0.11	0.18	0.20	0.22	0.13
ALT	0.17	0.11	0.19	0.24	0.23	0.06
P-value	NS	NS	NS	0.083	NS	0.026
Change in mass following 2nd sieving ($g\,kg^{-1}$)						
CON	7.77	9.40	−4.87	−0.20	−2.83	−12.40
ALT	13.83	8.90	1.40	2.17	−11.57	−18.07
P-value	0.074	NS	NS	NS	NS	NS
Soil organic C ($g\,kg^{-1}$)						
CON	15.64	16.75	17.17	16.49	16.12	15.98
ALT	15.95	17.89	18.53	17.68	16.84	17.40
P-value	NS	NS	NS	NS	NS	NS
Water stability of dry aggregates (%)						
CON	NM	14.8	27.9	44.0	66.3	NM
ALT	NM	14.2	23.3	44.3	46.3	NM
P-value		NS	NS	NS	NS	

NM = not measured, significant treatment effects at $P = 0.05$ and NS = not significant.

compared with CON (Table 6, change in mass following second sieving). Aggregates in groups 1 and 2 are susceptible to wind erosion. We did not observe large differences between treatments at the Mead site following first or second sieving (Table 6).

Distribution of C among aggregate groups was not uniform. The ALT system had greater SOC than the CON system for both Brookings (except group 6) and Mead (Table 6). Dry aggregates from Brookings were less stable in water than those from Mead and this might be expected because the Brookings soil contains $466\,g\,kg^{-1}$ sand and $275\,g\,kg^{-1}$ clay. In contrast, the Mead soil contains $60\,g\,kg^{-1}$ sand and $380\,g\,kg^{-1}$ clay. Aggregates from groups 4 and 5 (Table 6) under ALT management at Brookings were significantly (Table 6, group 4, $P = 0.09$) more stable than those formed under CON. This was contrary to our findings for the Mead soil (Table 6, group 5), where the data suggest greater stability under CON compared with ALT (differences were not significant).

Characterizing surface conditions by quantifying both aggregate distribution and stability is important because the manner in which aggregates break down on sieving (dry aggregate stability) reveals an important physical trait that could be used as an attribute of soil quality (SQ). Within the

same soil type, we think that aggregate stability is directly related to SOM status (J.L. Pikul, unpublished data 2005); however, we do not understand the temporal variation of this property within a system.

Values of MWD (calculated from aggregate distribution) provide a convenient way to show the dynamics of surface conditions with time as shown for Brookings (Fig. 4) and Mead (Fig. 5). Detailed analysis of aggregate properties, as conducted for the final soil samples (harvest 2002), at Brookings and Mead were laborious. Inspection of MWD values (Figs. 4 and 5) show that we conducted our detailed analysis of aggregates at a time when the MWD was close to an average value for the rotation cycle. For the Brookings site, MWD averaged across all dates was 8.3 mm for CON and 8.4 mm for ALT. Average MWD for the final sample was 7.0 mm for CON and 10.1 mm for ALT (Fig. 4). For the Mead site, MWD averaged across all dates was 5.0 mm for CON and 5.0 mm for ALT. Average MWD for the final sample was 6.2 mm for CON and 4.9 mm for ALT (Fig. 5).

DASD was expressed as MWD changes within a season and between seasons. Recognizing the temporal change in this surface soil property is important for understanding the dynamics of other soil properties linked to soil surface conditions such as water infiltration. Thus, MWD appears to be a useful trait for quantifying differences (at time of measurement) between management systems and as a measure to quantify temporal dynamics within a system.

Conclusions

Infiltration

Efficient water management requires attention to: (i) soil water use by crops (ii) reduction of water runoff, and (iii) opportunities to improve water recharge. Water intake rates are governed by surface and internal soil conditions and these conditions are ever-changing. Further, the inherently high spatial variability in water infiltration rates makes the interpretation of treatment effects difficult, especially in situations where tillage is used. We found no significant cropping system effects on infiltration for locations that had the same tillage system but differing cropping intensity or crop species in the cropping system. However, in the cases where no tillage was compared with tillage, infiltration was greater following tillage and declined over time in tilled systems. A cyclical pattern of infiltration rate was present for most cropping systems and locations, showing that a snap-shot of water infiltration (one-time measurement) would not be an appropriate SQ indicator because of significant temporal variation in infiltration rate. Measuring infiltration in wheel track and untracked parts of the field provides farmers with an understanding of how field operations affect this parameter and, in soils susceptible to reduced infiltration in traffic areas, will demonstrate the importance of controlling traffic patterns.

Bulk density and water-filled pore space

Long-term changes in BD indicative for use in SQ assessments would be difficult to establish and may be misleading if using a single sampling date, because BD changed significantly within each season and rotation. Multiple sampling dates throughout one or more rotational sequences are needed to ascertain long-term changes in BD.

Because most tillage operations on cropland are restricted to the upper 150 mm, and because soil root proliferation is typically greatest at shallow soil depths, BD measured near the surface was most sensitive to the effects of cropping systems. High BD (e.g., $>1.4\,g\,cm^{-3}$) near the surface, such as those observed at the Sidney location, are clearly undesirable. However, it may be difficult to ascertain if minor but significantly different BD observed at the surface for some of these treatment comparisons in fact lead to improved SQ. At lower soil depths, where BD more strongly influences root proliferation, a critical threshold criterion proposed by Arshad et al.[45] may be useful in evaluating these effects within an assessment framework for SQ. Tillage pans with narrow zones of high soil strength will also impede root proliferation. However, these features may sometimes be difficult to detect when the sampling depth increment is large.

WFPS, a function of BD and GW, fluctuated during the season and different rotational phases. We used a WFPS ratio of 0.6 as SAT value to delineate between water-limiting and aeration-limiting soil microbial processes. This approach provided a practical criterion for a systematic evaluation of distribution functions for the probability of exceeding a critical WFPS (with time, treatment, or depth). Systems having a high probability of exceeding SAT might then be viewed as having a detrimental effect on SQ. This criterion should be especially appropriate for locations having a combination of climate (cool and wet) and soil conditions (poorly drained) that pose a risk. For example, management at the Fargo location had a significant effect on WFPS and there was a high probability of exceeding SAT under no tillage when compared with tillage.

Identification of areas of a field having BDs exceeding threshold values for root elongation will be of interest to farmers. Management practices can be modified to address areas having high BDs due to activities such as wheel traffic or tillage. WFPS is an attribute that is more difficult to measure, but if areas of a field that exceed 0.6 WFPS for extensive periods of time can be identified, management practices such as improved drainage or reduced application of N fertilizer can be undertaken to lower the water content or decrease the potential for emission of greenhouse nitrogenous gases.

Soil aggregates

Greater MWD values were found under systems with greater cropping intensity and less tillage at Bushland and Fargo, respectively. A large MWD value represents an

aggregate size distribution having a large portion of large aggregates. Our measurements suggest that DASD (expressed as MWD) may be a sensitive indicator of change in soil condition. Systems with a greater fraction of material that is erodible by wind (defined as material < 0.84 mm diameter) have a small MWD and consequently a detrimental effect on SQ (judged in respect to wind erosion). Further, measurements at two locations show that aggregates < 0.84 mm diameter contain a higher C concentration than bulk soil, and soil loss due to erosion would result in accelerated C loss from the system.

DASD, expressed as MWD, changed within a season and between seasons for reasons that we do not understand. Recognizing the temporal change in this surface soil property is important for understanding the dynamics of other soil properties linked to soil surface conditions such as water infiltration. Quantifying surface conditions by measuring MWD may be a convenient way to reference position in the time course of a rotation. Thus, MWD appears to be a useful trait for quantifying differences (at time of measurement) between management systems and as a way to plan detailed soil investigations within a temporally dynamic system.

Analysis of the change in mass of dry aggregate fractions (dry aggregate stability), following a second rotary sieving, also shows promise as a sensitive indicator of SQ. Soil aggregates that easily disintegrate to aggregate fractions < 0.84 mm are erodible by wind. Consequently, this measurement of SQ reveals an important link between a physical laboratory measurement and an important field characteristic of soil, that is, its susceptibility to wind erosion.

WFPS and soil aggregate properties show promise as diagnostic attributes of SQ. Within the constraints of our study, we found differences between treatments at some locations that encourage further testing. Probability that WFPS exceeds a threshold value could serve as a decision tool (related to SQ) for evaluating tillage practice within crop management systems. Tillage is often viewed as a destructive practice in respect to SOM because accelerated loss of soil C is associated with increased tillage intensity. However, tillage also promotes soil surface drying and increased soil temperature, and these properties are important to stand establishment in the colder and wetter soils of the northern Great Plains. Thus, there is a contradiction between resulting SQ attributes directly related to tillage.

In northern, sub-humid regions of the Great Plains, wind erosion takes place. Soil movement is less than in the southern Great Plains, but the consequences are the same. Fine soil particles lost to wind erosion are also the richest in organic matter. There may be opportunity to develop functions related to SQ for various crop and tillage management options based on the DASD and the quality of SOM within the various size fractions. Since the fine soil particles that are susceptible to loss via wind erosion contain a proportionately higher C, farmers should adopt practices that protect the soil from erosion. In the Great Plains, maintaining crop residue on the soil surface using conservation tillage is the most efficient practice for protecting the soil.

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Cropping system influences on soil chemical properties and soil quality in the Great Plains

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Abstract

Soil management and cropping systems have long-term effects on agronomic and environmental functions. This study examined the influence of contrasting management practices on selected soil chemical properties in eight long-term cropping system studies throughout the Great Plains and the western Corn Belt. For each study, soil organic C (SOC), total N (TN), particulate organic matter (POM), inorganic N, electrical conductivity (EC), and soil pH were evaluated at 0–7.5, 7.5–15, and 15–30 cm within conventional (CON) and alternative (ALT) cropping systems for 4 years (1999–2002). Treatment effects were primarily limited to the surface 7.5 cm of soil. No-tillage (NT) and/or elimination of fallow in ALT cropping systems resulted in significantly ($P < 0.05$) greater SOC and TN at 0–7.5 cm within five of the eight study sites [Akron, Colorado (CO); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan, ND; and Swift Current, Saskatchewan (SK), Canada]. The same pattern was observed with POM, where POM was significantly ($P < 0.05$) greater at four of the eight study sites [Bushland, TX, Mandan, ND, Sidney, Montana (MT), and Swift Current, SK]. No consistent pattern was observed with soil EC and pH due to management, although soil EC explained almost 60% of the variability in soil NO_3-N at 0–7.5 cm across all locations and sampling times. In general, chemical soil properties measured in this study consistently exhibited values more conducive to crop production and environmental quality in ALT cropping systems relative to CON cropping systems.

Key words: management practices, soil organic matter, electrical conductivity, soil acidity

Introduction

In agricultural systems, soil and crop management decisions will affect soil quality, soil nutrient dynamics, and soil chemical properties. These management decisions include crop rotation, residue management, and the intensity and frequency of tillage. Bowman et al.[1] measured a 20% increase in soil organic C (SOC) in the surface soils of continuously cropped no-till managed dryland systems, which previously were managed under conventionally tilled wheat–fallow. Bowman et al.[1] correlated the increase in SOC to greater annualized crop yield (greater annualized C additions as crop residue). In their analysis, 57% of the variability in SOC at the 0–5 cm depth could be explained by a simple linear relationship with annualized grain yield. Similarly, Pikul et al.[2] measured significantly greater SOC in continuous corn than in a corn–soybean rotation near Brookings, South Dakota (SD). In that study, greater SOC was also thought to be related to the greater C additions in

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continuous corn than in corn–soybean systems. In continuous corn, more total C was fixed over time when compared to a corn–soybean rotation.

Tillage can degrade soil quality by mechanically destroying soil aggregates and exposing protected soil organic matter (SOM) to microbial attack. Tillage also increases residue mixing with the soil, thereby enhancing decomposition of both crop residues and native SOM. Conversely, many studies have linked SOM increases in no-tillage (NT) to an altered surface soil environment that favors slower SOM turnover and increased soil aggregation and aggregate-associated SOM relative to soil managed with conventional (CON) tillage[3,4].

For many years, loss of SOM in the Great Plains has been associated with tillage and summer fallow management[5,6]. Wood et al.[7] observed an increase in SOM at the surface soil (0–10 cm) after 4 years by changing the management practice from tilled wheat–fallow to NT and reducing fallow frequency. In general, management to reduce fallow frequency accompanied with NT and continuous cropping replenishes SOM[8].

Recently, interest has increased in identifying indicators appropriate for describing soil quality changes. Gregorich et al.[9] and Smith and Doran[10] suggested that soil total N (TN), SOC, inorganic N, P, and K, soil pH, and electrical conductivity (EC) are important measurements for assessing chemical aspects of soil quality. Particulate organic matter (POM), defined as a labile fraction of SOM, has also been used as a sensitive indicator of management effects on soil quality[11]. Cambardella and Elliott[11] suggested that decreased POM with increasing disturbance by tillage accounts for much of the SOM lost with cultivation of native sod. These chemical parameters as well as POM and SOC are important measures of soil quality because they provide indicators of soil nutrient supplying capacity (a critical soil function[10,12]), soil structure, SOM dynamics, and C sequestration.

The objective of this research was to assess the value of POM, EC, pH, inorganic N, TN, and SOC as attributes for comparing contrasting management practices over time in established long-term cropping system studies in the Great Plains and western Corn Belt. For each long-term study, a comparison was made between a CON management system that included fallow, tillage, and/or monocropping, and an alternative (ALT) management system that included reduced or conservation tillage, reduced incidence of fallow, and/or extended crop rotations over a period of 4 years.

Materials and Methods

Long-term cropping system studies at eight locations in the Great Plains were used in this study. The locations were near Akron, Colorado (CO); Brookings, SD; Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan, ND; Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada. At each location, plots representing the traditional CON management practice were compared to an ALT management practice (Table 1). Detailed information about soil characteristics and management practices at each location is provided in Varvel et al.[13].

To assess soil chemical properties, composite soil samples were collected three times a year from three replications of each treatment in CON and ALT systems at each location. Soil samples were collected three times each

Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings, SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW-WW-SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied, N fertilizer application rate based on soil test results.
[2] Abbreviations: A, alfalfa; C, corn; DW, durum spring wheat; F, summer fallow; L, lentil; M, proso millet; OCL, oat + clover; P, field pea; SB, soybean; SO, sorghum; SU, sunflower; SW, spring wheat; WW, winter wheat.

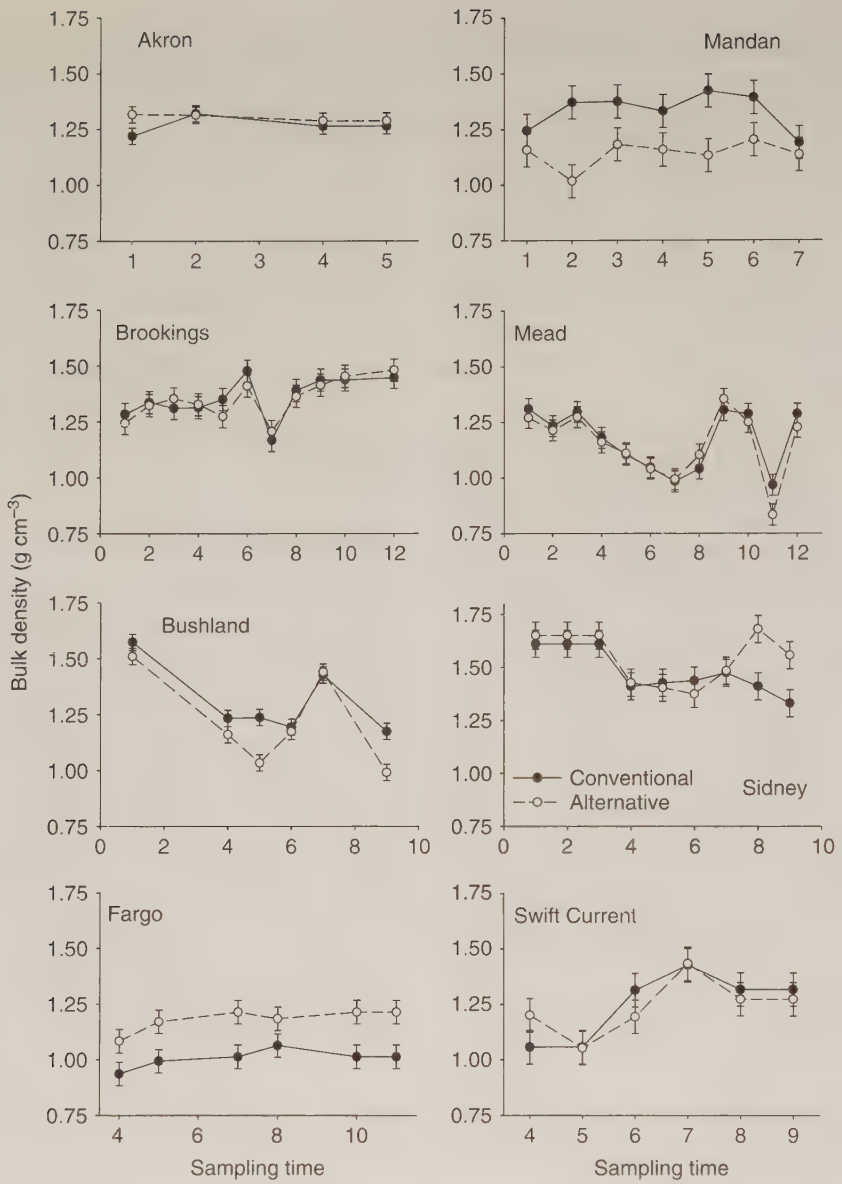

Figure 1. Soil bulk density (g cm^{-3}) in the 0–7.5 cm depth as a function of sampling time (multiple years) under the conventional and alternative management systems at eight locations in the Great Plains. Bars represent 1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; and post-harvest = 3, 6, 9, and 12.

year from each replicate of the treatments (for details of the sampling method, see Varvel et al.[13]). A total of 15–18 cores were collected to provide 500 g of oven-dry soil at each site on each sampling date. The actual mass of oven-dried soil and the volume of soil collected (calculated using the soil probe diameter, number of cores, and depth increment) were used to calculate bulk density. Upon collection, samples were saved in double-lined plastic bags and placed in cold storage (4°C) until processing.

Samples were air-dried and passed through a 2-mm sieve prior to analyses. Each site performed its analysis. Soil total C and TN were determined by dry combustion using a Leco IR C/N analyzer (CHN-2000, St. Joseph, MI, USA, 49085) or a Carlo Erba C/N analyzer (Carlo Erba Instruments, Milan, Italy) on soil ground to pass a 0.106-mm sieve. To determine SOC, inorganic C was subtracted from total C. Inorganic C was measured on soils with a pH $\geqslant$ 7.2 by quantifying the amount of CO_2 produced after application of dilute HCl stabilized with $FeCl_2$[14]. Inorganic N was determined by extracting 10 g of soil with 100 ml of 2 *M* KCl after shaking for 1 h at 300 rpm on an orbital shaker. The supernatant was filtered through Whatman filter paper No. 2 and stored at 4°C until analyzed colorimetrically for NH_4-N and NO_3-N using the method described by Keeney and Nelson[15]. Soil pH and EC were determined using soil : water in the ratio 1 : 1 (w : w)[10].

POM was determined using the procedure of Cambardella et al.[16]. Briefly, POM was measured by adding 90 ml

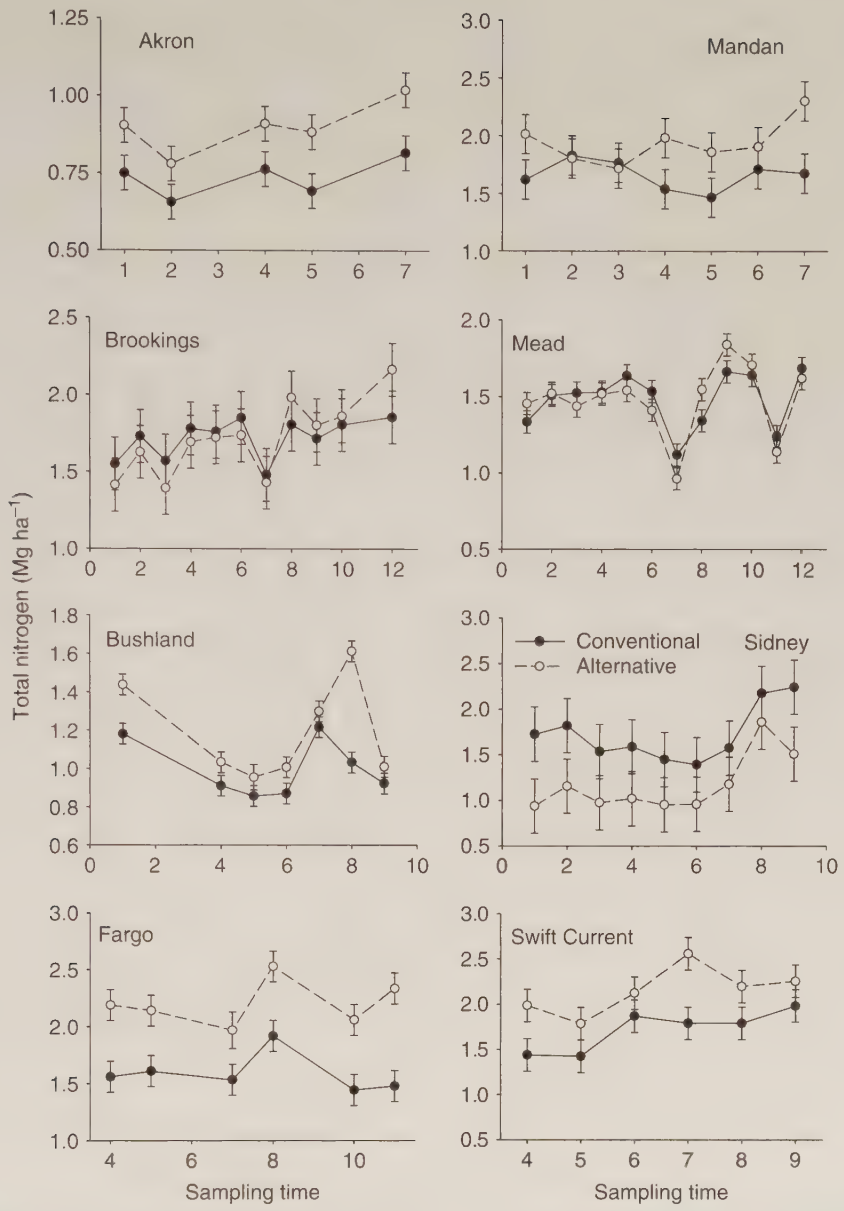

Figure 2. Total soil N (Mg N ha^{-1}) in the 0–7.5 cm depth as a function of sampling time (multiple years) under the conventional and alternative management systems at eight locations in the Great Plains. Bars represent 1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; and post-harvest = 3, 6, 9, and 12.

of 0.5% $Na(PO_3)_x$ to 30 g of air-dried soil in a screw-cap plastic vial. Vials were capped and placed on a reciprocating shaker overnight at 120 rpm. The contents of each vial were then transferred to a set of nested sieves having mesh sizes of 0.5 and 0.053 mm, where the material retained on each sieve was rinsed until all material smaller than the mesh size had been washed through. The material retained on each sieve was transferred into an aluminum weighing pan and dried to a constant weight at 55°C. The dried mass of the 0.5–2.0 and 0.053–0.5 mm fractions was recorded to the nearest milligram. Loss-on-ignition (LOI) for the total soil and POM was determined by mass difference after 4 h in a muffle furnace at 450°C. Air-dried soil (5–10 g) was used for LOI of total soil. POM associated with the two different size fractions was calculated using the equation:

$$\text{mg POM g}^{-1}\text{ soil} = \frac{\text{initial mass of the fraction} - \text{mass of the fraction after ignition}}{\text{initial mass of the soil}} \times \frac{1000\text{ mg}}{\text{g}}. \quad (1)$$

POM as a percentage of SOM was calculated using the equation.

$$\text{POM as \% of SOM} = \frac{\sum \text{mg of the fraction lost on ignition}}{\text{mg of total soil lost on ignition}} \times 100. \quad (2)$$

Data are reported on a volumetric basis by adjusting data for differences in bulk density. Data were analyzed using a

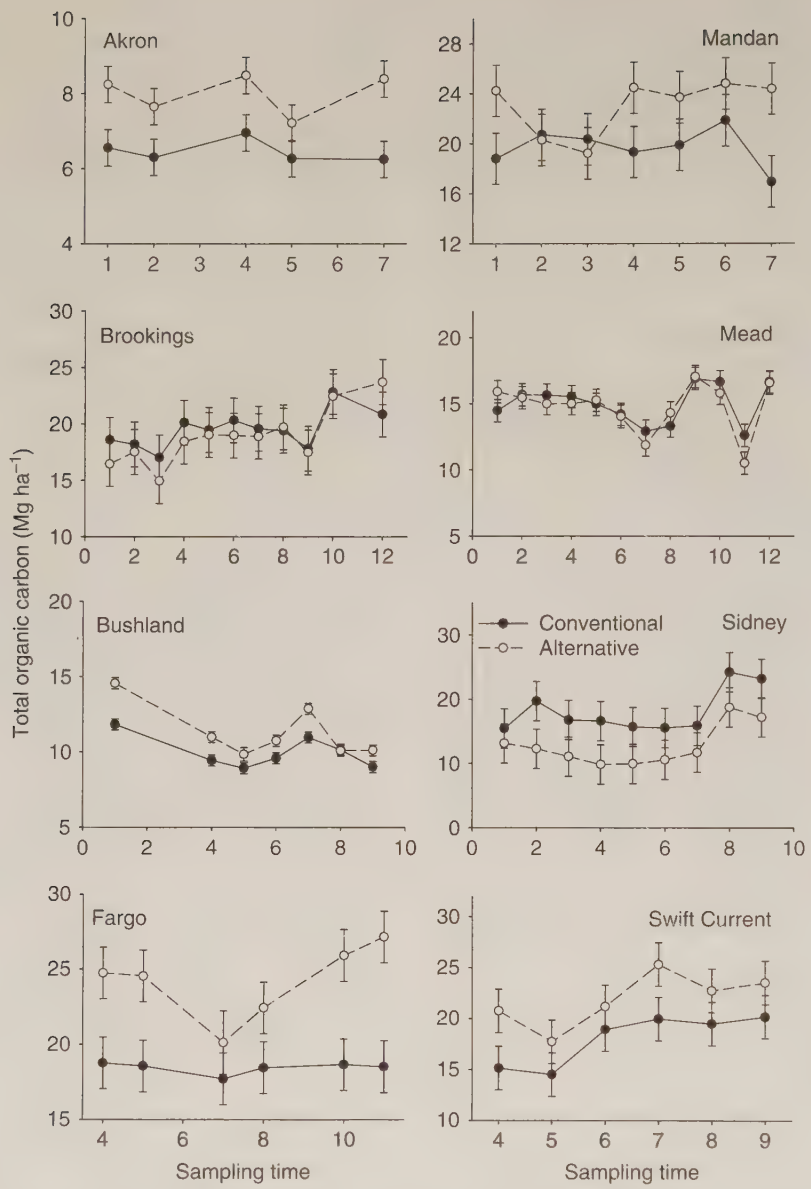

Figure 3. Total soil organic carbon (Mg C ha^{-1}) in the 0–7.5 cm depth as a function of sampling time (multiple years) under the conventional and alternative management systems at eight locations in the Great Plains. Bars represent 1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; and post-harvest = 3, 6, 9, and 12.

completely randomized split plot design with system as the main plot and sampling time as the subplot. The analysis of variance *F*-tests were used to determine treatment differences and *F*-protected *t*-tests were used on pairwise comparisons as a follow-up for any significant finding. The analysis of variance and mean separation difference were conducted for each site using Proc Mixed in SAS[17]. Soil depths were also analyzed independently. All results were considered significantly different at $P < 0.05$ unless noted otherwise.

Results and Discussion

Management treatments affected soil TN, NO_3-N, SOM (both organic C and LOI), POM, EC, and pH in the 0–7.5 cm increment at most study locations. Treatment effects in measured variables in the 7.5–15 and 15–30 cm increments were less commonly observed and when present were usually at locations where the CON and ALT differed in tillage intensity (Brookings, Fargo, Mandan, and Mead). Temporal variation was common for all measured variables in all depth increments and at all locations. A significant treatment by time interaction was infrequently observed. There were no consistent trends for the effect of time, and the observed temporal variation was likely due to changes in bulk density (BD) among growing seasons. BD (0–7.5 cm depth) exhibited temporal variability at Brooking, Bushland, Mead, Sidney, and Swift Current (Fig. 1). The effect of time on BD was significant ($P < 0.05$). In reality, changes in BD developed slowly

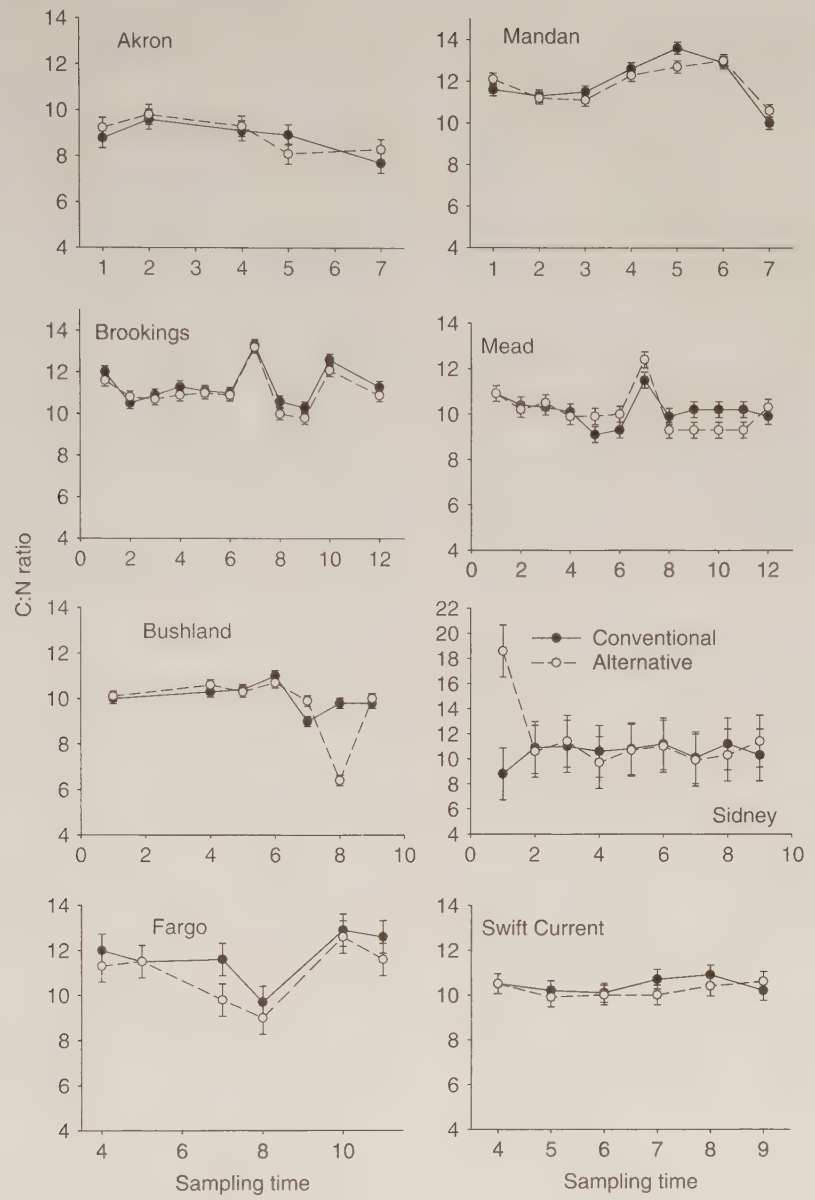

Figure 4. Soil C : N ratio in the 0–7.5 cm depth as a function of sampling time (multiple years) under the conventional and alternative management systems at eight locations in the Great Plains. Bars represent 1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; and post-harvest = 3, 6, 9, and 12.

and without tillage require more than a single growing season to change. Many factors can affect BD measurement. Factors such as soil water content, soil compaction, sampling method, and operator technique need to be considered when sampling for BD. The variations in BD that we observed in this experiment, at individual locations, were probably due to the factors mentioned earlier and, in some cases, were artifacts of soil condition by sampling technique interaction. In general, variation exhibited by the measured variables makes it impossible to recommend a single best time to sample when assessing management impacts on chemical soil properties. Dynamic assessments are essential for separating the effect of management practices on soil properties from variation exhibited by these properties due to weather.

Alternative cropping systems significantly increased TN (0–7.5 cm depth) at Akron, Bushland, Fargo, Mandan, and Swift Current (Fig. 2). TN in the 0–7.5 cm depth exhibited temporal variability at all locations except Mandan. The temporal pattern exhibited by TN in both treatments at each location was similar, suggesting that the temporal variability observed was likely caused by something affecting both treatments. It is conceivable that part of the variability in TN measured is due to variability in BD. TN exhibited temporal variability in the 7.5–15 and 15–30 cm depth increments at all locations. Treatment differences (averaged across all dates) in the lower two depths were observed at Fargo (1.71 Mg N ha^{-1} in the CON treatment versus 2.03 Mg N ha^{-1} in the ALT treatment) and Swift Current (1.72 Mg N ha^{-1} in the CON treatment versus

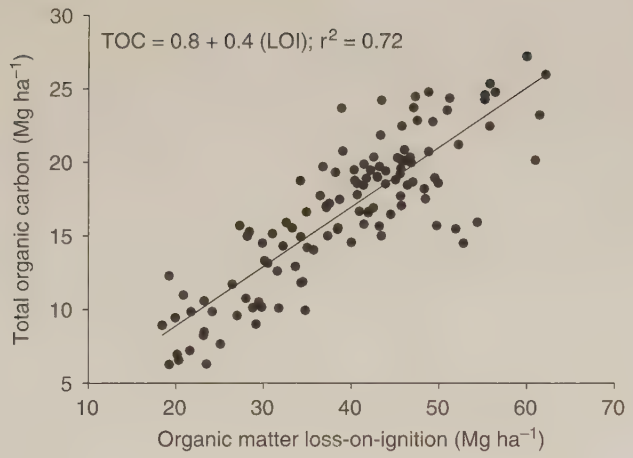

Figure 5. Relationship between two methods of measuring soil organic matter using soils from the 0–7.5 cm depth from contrasting management systems at eight locations in the Great Plains.

1.97 Mg N ha^{-1} in the ALT treatment) for the 7.5–15 cm increment and at Bushland (1.77 Mg N ha^{-1} in the CON treatment versus 2.03 Mg N ha^{-1} in the ALT treatment) for the 15–30 cm increment. Higher TN in the ALT treatment resulted from more intensive cropping accompanied by a decrease in tillage intensity or incidence of fallow.

Soil NO_3-N was highly dynamic throughout the sampled profile with a significant effect of time at all locations. Treatment by time interactions were also significant at all locations except Swift Current. In addition to weather, fertilizer additions of N and crop uptake contributed to the temporal variability observed. Differences in crop rotation and presence of fallow likely contributed to treatment differences (data not shown). Nitrate N is an important crop nutrient and also has potential for contamination of surface and ground water when transported in runoff or leaching. Optimal N management requires that residual NO_3-N be accounted for in making fertilizer recommendations and that realistic yield goals be used for determining appropriate fertilizer rates.

SOC was greater in the 0–7.5 cm depth of the ALT treatment than in the CON treatment at Akron, Bushland, Fargo, and Swift Current. The increase in SOC in the 0–7.5 cm increment was due to reduced tillage intensity at Akron and Fargo, or to a reduction in the incidence of fallow at Akron, Bushland, and Swift Current. The only treatment difference observed in the lower two increments occurred at Fargo (19.5 Mg C ha^{-1} in the CON treatment versus 23.2 Mg C ha^{-1} in the ALT treatment) in the 7.5–15 cm depth. Wood et al. (1991)[7] observed an increase in SOC after imposing NT and intensive cropping in soil previously managed with tillage under wheat–fallow management. Temporal variation in TOC was observed at Brookings, Bushland, Mead, Sidney, and Swift Current. There were similarities between the two treatments in the exhibited temporal pattern, suggesting that the source of the temporal variation was likely affecting both treatments similarly (Fig. 3). Apparently, the variations in TOC for both treatments at various sampling times are an artifact of BD or sampling procedure.

Soil C : N ratio (0–7.5 cm depth) was significantly ($P < 0.05$) affected by time except at Sidney and Swift Current (Fig. 4). Temporal variability of C : N ratio was also observed at all locations except Akron and Swift Current. The temporal pattern exhibited by C : N in both treatments, at each location, was similar (except one sampling time in Bushland, Fargo, and Swift Current), suggesting that the temporal variability observed was likely caused by something affecting both treatments. As with BD, changes in soil C : N ratio are slow to develop and may take years to manifest. Many factors can affect C : N measurement: sampling procedure, grinding method, sample weighing accuracy, instrument sensitivity, and most importantly the presence of plant residues. The reduction in C : N ratio with CON treatment in one sampling date (Fig. 4) at Bushland and Fargo was probably due to instrument sensitivity and/or variability in measurement technique.

When SOM was determined using LOI, treatment differences were less frequently detected than with SOC, with differences in the 0–7.5 cm depth apparent only at Fargo. Treatment differences approached significance at Akron, Bushland, Mandan, and Swift Current. While the LOI method of determining SOM appears less sensitive, there was a strong correlation between total organic carbon (TOC) and organic matter measured using LOI (Fig. 5). Since the LOI method requires less sophisticated equipment, the strong correlation and the trend toward treatment differences suggest that this method has merit for monitoring long-term changes in SOM. In this study, C lost using LOI methods represent 40% of SOC, which is different from the 58% traditionally used, but not unusual.

Treatment differences in SOC and TN were associated with differences in tillage practices between the treatments. This observation agrees with Halvorson et al.[18], where an increase in SOC was observed as tillage intensity decreased within an annual cropping system. Tillage reduces SOC and TN by increasing residue contact with soil microbial populations, which enhances residue oxidation and decomposition[19–21]. Additionally, Blevins and Frye[21] reported that tillage promotes soil erosion and deterioration of soil structure due to destruction of soil aggregates and increased soil compaction. Conversely, NT increases SOC and TN in the surface increment when the soil is not disturbed and residue is not incorporated. With NT, soil water content in near-surface soil tends to be greater, resulting in a proliferation of root growth, which acts to increase SOC and TN. Roots near the soil surface also stabilize soil aggregates by binding them together, thereby reducing the erosion potential of the surface soil and its resident C and N[20,21].

There were no differences in TN (Fig. 2) and SOC (Fig. 3) between the CON and ALT treatments at Brookings and Mead. At these locations, both ALT and CON treatments were tilled (Table 1). The fact that both

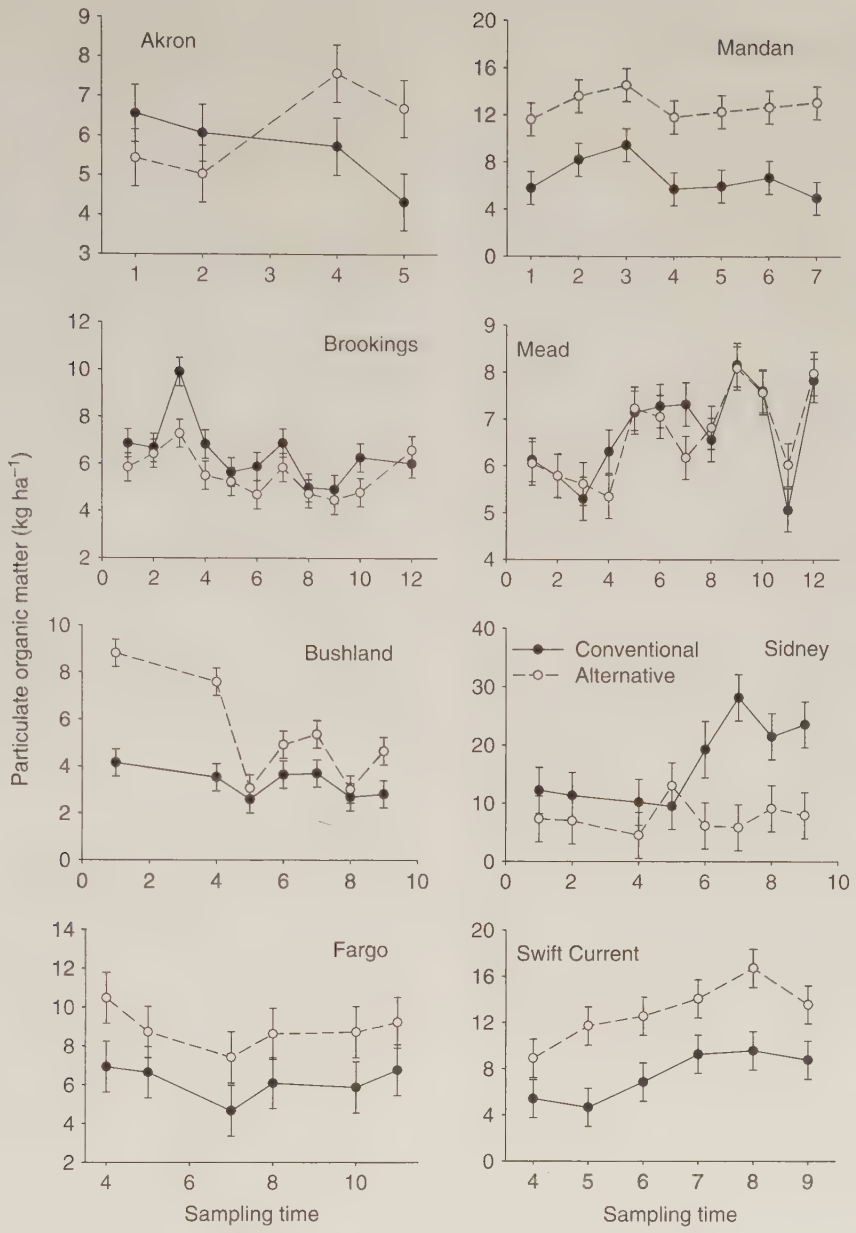

Figure 6. Particulate organic matter (kg ha^{-1}) in the 0–7.5 cm depth as a function of sampling time (multiple years) under the conventional and alternative management systems at eight locations in the Great Plains. Bars represent 1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; and post-harvest = 3, 6, 9, and 12.

CON and ALT treatments were tilled may have masked the cropping sequence differences.

At Swift Current, TN (Fig. 2) and SOC (Fig. 3) were greater in the ALT treatment than in the CON treatment. The increase associated with the ALT treatment is probably due to a reduction in the incidence of fallow, since NT was used in both the CON and ALT treatments (Table 1). In general, summer fallow enhances SOM decomposition, thereby decreasing SOC[8]. Additionally, C additions to the soil are lower in summer fallow systems since a crop is growing every other year[22].

POM was greater in the 0–7.5 cm depth of the ALT treatment than the CON treatment at Bushland, Mandan, Sidney, and Swift Current (Fig. 6). POM was 44% greater in soils from the ALT treatment than in soils from the CON treatment at Fargo ($P = 0.06$). Overall, the increase in POM within the ALT system was associated with a reduction in tillage intensity and fallow frequency. Beare et al.[23] observed 20% greater POM in NT managed soils compared to conventionally tilled soils. Treatment differences in POM in the 7.5–15 cm increment were observed at Mandan (4.0 kg ha^{-1} in the CON treatment versus 6.9 kg ha^{-1} in the ALT treatment) and at Swift Current (5.2 kg ha^{-1} in the CON treatment versus 7.9 kg ha^{-1} in the ALT treatment). Treatment differences in POM in the 15–30-cm depth were observed at Swift Current (4.4 kg ha^{-1} in the CON treatment versus 6.8 kg ha^{-1} in the ALT treatment). Temporal dynamics were exhibited by POM in all soil

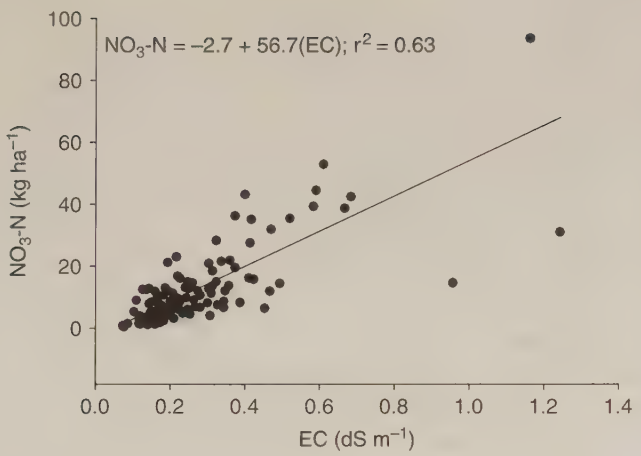

Figure 7. Relationship between soil EC (dS m^{-1}) and NO_3-N content (kg N ha^{-1}) using soil from the 0–7.5 cm depth from contrasting management systems at eight locations in the Great Plains.

depths. In the 0–7.5 cm depth increment, the temporal pattern exhibited by POM was similar between the two treatments, suggesting that a factor such as weather, or BD, was affecting POM similarly in both treatments. In our study, temporal and treatment responses mirrored those of SOM, suggesting that the POM may be a component of SOM that is sensitive to management. The method of determining POM[16] used in this study does not require sophisticated equipment and will be useful for land managers monitoring management influences on SOM.

Soil EC exhibited temporal variability at all locations and in all soil depths. Treatment differences were observed at Brookings, Fargo, and Mead for the 0–7.5 and 7.5–15 cm depths and at Mandan for the 15–30 cm depth. In these non-saline soils, the most likely source of variation in EC is fluctuating NO_3-N content. Soil NO_3-N and EC in the 0–7.5 cm depth were positively correlated (Fig. 7). Smith and Doran[10] also observed a positive correlation between soil EC and NO_3-N ($r = 0.84$ for fall sampling and 0.74 for spring sampling). Since soil EC is extremely easy and inexpensive to measure, these results suggest that EC may serve as a useful tool for land managers to use for estimating NO_3-N content in non-saline soils.

Soil pH exhibited temporal dynamics at all locations in at least one depth increment. Soil pH differed between management practices in the 0–7.5 and 7.5–15 cm depth at Fargo and Mead. Treatment differences in pH were likely due to use of ammoniacal fertilizer. Bowman and Halvorson[24] reported that surface applications of ammoniacal fertilizers tend to decrease soil pH over time. The pH decrease was attributed to nitrification of the ammoniacal N source in excess of nitrate uptake by crops. All of the locations receive annual applications of ammoniacal N to satisfy the N crop requirement. With NT, most of the N fertilizer application is surface applied. Over time, the increase in NO_3-N would be expected to correspond to a decrease in soil surface pH. Liebig et al.[25] found a similar correlation between soil pH and residual NO_3-N.

Conclusions

Chemical soil properties measured in this study (TN, POM, and TOC) were consistently greater in the ALT treatment than in the CON treatment. Improvements in soil chemical properties in the ALT treatment were attributed to a reduction in tillage intensity and incidence of fallow. Differences between the two treatments were usually only detected in the surface 7.5 cm, underscoring the importance of sampling this near-surface soil depth for assessing management effects on soil chemical properties. Many of the attributes measured in this study exhibited temporal variability, with much of the variability being associated with weather and related changes in crop status or soil bulk density estimation during the growing season. There does not appear to be a single sampling time that can be recommended to compare short-term management effects. Instead, dynamic assessments are essential for understanding management impacts on soil quality in the context of specific soil functions.

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Cropping system effects on soil biological characteristics in the Great Plains

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Abstract

Soil biological quality can affect key soil functions that support food production and environmental quality. The objective of this study was to determine the effects of management and time on soil biological quality in contrasting dryland cropping systems at eight locations in the North American Great Plains. Alternative (ALT) cropping systems were characterized by greater cropping intensity (less fallow), more diverse crop sequences, and/or reduced tillage than conventional (CON) cropping systems. Soil biological properties were assessed at depths of 0–7.5, 7.5–15, and 15–30 cm from 1999 to 2002 up to three times per year. Compared to CON, ALT cropping systems had greater microbial biomass and potentially mineralizable N. ALT cropping systems also had greater water stable aggregates in the surface 7.5 cm, but only at four locations. Total glomalin (TG), an organic fraction produced by fungi associated with aggregate stability, differed only at one location (Mandan), where the ALT cropping system had 27% more TG than the CON cropping system. Fatty acid methyl ester (FAME) profiles were highly location dependent, but total extracted FAME tended to be higher in ALT cropping systems. Soil biological properties fluctuated over time at all locations, possibly in response to weather, apparent changes in soil condition at sampling, and the presence or absence of fallow and/or legumes in rotation. Consequently, preplant and post-harvest sampling, when weather and soil conditions are most stable, is recommended for comparison of soil biological properties among management practices. Overall, ALT cropping systems enhanced soil function through: (1) improved retention and cycling of nutrients and (2) maintenance of biodiversity and habitat, implying improved agro-ecosystem performance over time.

Key words: cropping systems, soil biology, Great Plains, soil quality

Introduction

Soil biota mediate important ecosystem processes such as energy flow, nutrient cycling, and water infiltration and storage[1]. Improved soil management may enhance the activities of soil flora and fauna, including decomposition of organic residues, assimilation and release of plant nutrients, creation of biopores, and production of compounds in soil thought to enhance aggregate stability[2–5]. Collectively, soil biota affects both agricultural productivity and environmental quality and, therefore, warrants careful consideration when evaluating the sustainability of cropping systems.

Cropping systems influence soil biota predominately through the kind and quantity of plant residue food sources they provide, and their impacts on the soil physical and chemical environment[3]. Crop type and sequence, cropping intensity, tillage and residue management, and fertilization represent management components that shape the environment in which soil biological activity takes place. However, the impacts of cropping systems are greatly altered by soil type and climate. Furthermore, cropping system effects on soil biota may take a considerable time to accrue to the

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point that they become measurable. In a review of soil biological characteristics in conventional (CON) and alternative (ALT) agricultural systems, Ryan[6] found that management practices may need to be in place for more than 10 years before they have a consistent influence on the soil biological community. Such an influence may take even longer when systems have a relatively low level of production and few inputs, due to limiting factors such as low rainfall or extreme temperatures[6]. Interestingly, these limiting factors characterize the climate of the Great Plains[7,8].

Cropping systems with intensive crop sequences and/or reduced tillage in the Great Plains have been found to possess more soil microbial biomass[9–11], potentially mineralizable N (PMN)[11–14], and total glomalin (TG)[15]. Such trends in soil biological characteristics are attributed to greater crop residue, root mass, and soil organic matter (SOM) accumulation in the soil surface of these systems. Specific responses of soil microbial communities to management practices in the Great Plains indicate that no-till, relative to conventional tillage, results in increased fungal abundance[16], higher populations of denitrifying bacteria[17], and greater ester- and phospholipid-linked fatty acid methyl esters (FAME) under fallow conditions[18]. These results underscore the capacity of no-till to favor the growth and activity of soil micro-organisms that can improve soil structure but also increase gaseous N loss by denitrification.

In 1999, a multi-location study was initiated to evaluate a number of soil physical, chemical and biological properties proposed for assessing soil quality[19]. The objectives of this study were to (1) quantify temporal dynamics of soil quality attributes in established cropping systems; (2) assess impacts of contrasting management on soil quality attributes; and (3) evaluate recently developed methods for assessing soil quality (e.g., microbial biomass by microwave irradiation, FAME and TG). The study's objectives allowed for the evaluation of management impacts on a consistent set of soil biological properties across multiple locations over time, which, to our knowledge, has not been conducted in the Great Plains.

Materials and Methods

Description of locations and treatments

Contrasting management treatments within eight long-term cropping system experiments throughout the Great Plains were selected for the study (Table 1). Experiments were located near Akron, Colorado (CO); Brookings, South Dakota (SD); Bushland, Texas (TX); Fargo, North Dakota (ND); Mandan, ND; Mead, Nebraska (NE); Sidney, Montana (MT); and Swift Current, Saskatchewan (SK), Canada, and had been conducted from 9 to 32 years upon initiation of this study. Contrasting treatments were selected within each experiment representing CON and ALT cropping systems, with the latter characterized by reduced tillage, reduced occurrence of fallow, and increased crop diversity. In addition to the established treatments, relic areas under undisturbed native perennial vegetation were evaluated at four locations (Fargo, Mandan, Mead, and Sidney). A detailed description of locations and treatments is provided elsewhere[20].

Sampling method

Soil samples were collected up to three times per year over a period of 4 years at each location. Samples were collected

Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/Soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings, SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW–WW–SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied, N-fertilizer application rate based on soil test results.
[2] Abbreviations: A, alfalfa; C, corn; DW, durum spring wheat; F, summer fallow; L, lentil; M, proso millet; OCL, oat + clover; P, field pea; SB, soybean; SO, sorghum; SU, sunflower; SW, spring wheat; WW, winter wheat.

prior to planting, at peak crop biomass, and after harvest in the same plots throughout the duration of the study. Two types of soil sample were collected from each plot at each sampling time. The first sample was collected to a depth of 30 cm in increments of 0–7.5, 7.5–15, and 15–30 cm with a step-down probe. The second soil sample was collected from the surface 0–7.5 cm for glomalin concentration, wet aggregate stability, and aggregate-size distribution, using a shovel or trowel in such a manner as to maintain aggregate integrity. Upon collection, the first set of samples was placed in cold storage at 4°C until processing, while the second set was immediately air-dried at <35°C for 3 or 4 days. A detailed description of the sampling and soil processing method can be found elsewhere[20].

Laboratory evaluations

Microbial biomass and PMN. Microbial biomass analyses were conducted within 1 week of receipt of samples to the laboratory. Microbial biomass C (MBC) was estimated by the microwave irradiation method using a 10-day incubation of irradiated and non-irradiated subsamples[21] with CO_2 production determined by gas chromatography[22]. Headspace of the non-irradiated samples was flushed with air, resealed, and incubated for an additional 10 days for estimates of mineralizable C and N. MBC was calculated from the difference between CO_2 released from irradiated and non-irradiated soils. Metabolic quotient (qCO_2) was calculated as mg of CO_2 respired per mg of total MBC[23]. Microbial biomass N (MBN) was estimated from the 10-day mineral N flush between irradiated and non-irradiated soils[24].

PMN was estimated from the NH_4-N accumulated after a 7-day anaerobic incubation at 40°C using 5 g oven-dried equivalent of field moist soil[25]. Ammonium before and after the incubation was estimated from 1 : 10 soil : KCl (2 *M*) extracts by an indophenol blue reaction[26].

Aggregate stability and glomalin. Air-dried bulk soil was sieved to segregate the 1–2 mm size aggregates. Aggregates were premoistened with deionized water by capillary action for 10 min and then subjected to wet sieving for 5 min[27]. Soil particles passing through a 0.25 mm sieve were dried at 75°C and weighed. The material remaining on the 0.25 mm sieve was dispersed with 5% sodium hexametaphosphate and the coarse material was washed with deionized water, dried, and weighed. The initial and final weights of aggregates were corrected for the weight of coarse particles (>1 mm).

Glomalin was extracted from 1 g of aggregates using 50 m*M* citrate, pH 8.0, for 1 h cycles at 121°C until the supernatant was straw-colored, an indication that all of the glomalin had been removed. Supernatants for each soil sample were pooled, mixed, and an aliquot was centrifuged at 10,000 g for 3 min. Protein in the supernatant was detected by the Bradford dye-binding assay with bovine serum albumin as the standard[28]. Concentration of glomalin was extrapolated to mg g^{-1} of aggregated soil particles by correcting for the dry weight of coarse fragments >1 mm included in the weight of aggregates and for the volume of extractant. As a supplement to glomalin analysis, extractable Fe in bulk surface soil was estimated using inductively coupled plasma atomic emission spectroscopy after extraction by diethylenetriaminepentaacetic acid (DPTA)[29].

FAME extraction. Fatty acids were extracted from 5 g air-dried soil samples in acid-washed glassware using the Microbial Identification, Inc. standard protocol[30]. Samples were analyzed using a Varian 3800 gas chromatograph with a 30 m Rtx-2330 capillary column and a Saturn 2000 mass spectrometer (MS) as the detector (Varian, Inc., Palo Alto, CA, USA). Fatty acids were identified and quantified by comparison of retention times, MS fragments, and peak areas to components of the Supelco 37 Component FAME mix (#47885-U; Supelco, Inc., Bellefonte, PA, USA) and several individual standards (Sigma M-2799, H-3523, M-7656, M-6656, and M-3289; Sigma–Aldrich, St. Louis, MO, USA). Individual peak data for each fatty acid were converted to molar percentages by dividing peak area by the fatty acid molecular weight, then dividing by the total molar area of all fatty acids identified in the sample.

Statistical analyses

Microbial biomass, PMN, water-stable aggregates (WSAs), and glomalin were evaluated within locations using appropriate models in PROC MIXED[31]. Evaluations were conducted by depth using treatment and time as fixed effects and replication as a random effect. Time represented effects within years (preplant, peak biomass, and post-harvest) and over years (1999–2002) and was assigned a dummy variable from 1 to 12 corresponding to the 12 separate sampling times. Additionally, biological properties were evaluated by grouping locations within their respective soil moisture regimes. For this evaluation, Brookings, Fargo, and Mead were grouped into an udic moisture regime, while Akron, Bushland, Mandan, Sidney, and Swift Current were grouped into an ustic moisture regime. Evaluations by soil moisture regime were conducted with PROC MIXED using data only from the preplant sampling time and 0–7.5 cm depth. Relationships between soil biological properties and relevant soil chemical and physical parameters as well as management, climatic, and sampling factors were identified by linear regression analysis using SAS[32] or Statistix (Analytical Software, Tallahassee, FL, USA).

Potential biomarker FAMEs[33,34] were analyzed individually or in small groups by depth using an appropriate model in PROC MIXED. Molar percentages of FAMEs were used in principal components analysis (PCA) across all locations, times, and depths using data from 2000 to compare primary factors affecting FAME profiles[35]. Factor

Table 2. Fatty acid methyl esters (FAMEs) used in principal components analysis (PCA) with eigenvector loadings >|0.20|. Positive or negative loadings farther from 0.0 have a greater relative effect on PC ratings.

PC 1		PC 2		PC 3	
FAME[1]	Loading	FAME	Loading	FAME	Loading
12:0[2]	0.34	14:0 *3OH*	0.29	15:0 *iso*	0.35
13:0 *iso*	0.31	16:1 ω9*c*	0.34	15:0 *anteiso*	0.39
13:0 *branched A*	0.22	17:1 *iso*	0.22	16:0 *iso*	0.33
14:0	0.28	18:0 *iso*	0.22	16:0 *2OH*	−0.28
16:1 ω7*c*	−0.21	18:0 *branched A*	−0.28	17:0 *branched C*	−0.22
17:0 *anteiso*	−0.21	18:2 ω6*c*	0.27	17:1 *branched A*	−0.27
17:0 *branched A*	−0.23	19:0 *cyclo*	−0.28	18:1 ω9*t*	−0.28
17:0 *branched A*	−0.23				
17:0 *cyclo*	0.21				
18:0 *branched A*	−0.26				

[1] Fatty acids are identified by the number of carbon atoms, the number of double bonds and the position of the first double bond from the methyl (ω) end of the molecule. Suffixes for fatty acids designate the existence of branching (*A*, *B*, *C*, *iso* and *anteiso*) or the presence of cyclopropane (*cyclo*) or hydroxy (*OH*) fatty acids. *Cis* and *trans* isomers are indicated by *c* and *t*, respectively[53].
[2] General characterization of fatty acids by organism type is as follows: hydroxy- and cyclo-FAMEs, Gram-negative bacteria; iso- and anteiso-FAMEs, Gram-positive bacteria; polyunsaturated C_{18} FAME, fungi; polyunsaturated C_{20} FAME, protozoa; other FAME, microeukaryote origin.

descriptions and eigenvector loadings for the PCA are presented in Table 2.

Results and Discussion

Microbial biomass C and N

Management affected MBC, MBN, and MBC : SOC, but not qCO_2 (Table 3). The ALT treatment at Fargo, Mandan, Mead, and Swift Current had a greater MBC and a higher ratio of MBC : SOC when compared to the CON treatment in at least part of the surface 30 cm (Table 3). At Brookings, Bushland, Fargo, Mandan, and Mead, the ALT treatment had greater MBN compared to the CON treatment. Increases in MBC, MBN, and MBC : SOC are indicative of improvements in SOM quality[36,37] and reflect an enhancement of a soil biological condition favoring internal recycling of nutrients[3]. Values of qCO_2 ranged from 0.02 to 0.16 mg CO_2 mg^{-1} MBC day^{-1}, with the highest values tending to occur at 0–7.5 cm.

Tillage, cropping frequency, and crop diversity were major drivers of microbial biomass levels within locations. At Fargo, where moldboard plow and no-till were contrasted within a spring wheat–field pea crop sequence, MBC, MBC : SOC, and MBN were 2-, 1.6-, and 1.5-fold greater, respectively, in the top 7.5 cm of the no-tilled plots compared to the moldboard plowed plots. Increased soil disturbance by tillage has been found to result in lower MBC and MBN[38–41], thereby reducing soil nutrient cycling potential. A combination of no-tillage and continuous cropping in the ALT treatment at Mandan contributed to 1.5- and 1.6-fold greater MBC and MBN than in the CON treatment (tandem disk/chisel plow, crop–fallow) at 0–7.5 cm. At Swift Current, where the tillage treatment was the same in CON (wheat–fallow) and ALT (wheat–lentil) treatments, there was 1.2–1.7-fold greater levels of MBC and MBC : SOC in the surface 30 cm of the wheat–lentil rotation compared to wheat–fallow. Elimination of fallow may have also contributed to differences in microbial biomass at Bushland, where the continuous wheat treatment had more MBN than a wheat–sorghum–fallow treatment at all three depth increments. MBC and MBN were greater in 4-year crop rotations (ALT) than continuous corn (CON) in the surface 15 cm at Brookings and Mead, underscoring the importance of crop diversity in enhancing the internal soil nutrient cycling potential in corn-based cropping systems.

The perennial vegetation areas at Fargo, Mandan, Mead, and Sidney generally had more MBC, MBN, and MBC : SOC compared to the cropped treatments (Table 3). Specifically, MBC, MBN and MBC : SOC were 2.3-, 2.1-, and 1.7-fold greater, respectively, under perennial vegetation compared to CON treatments when averaged across the four locations and three depth increments. Differences between perennial vegetation areas and ALT treatments were less pronounced (2.0-, 1.9-, and 1.5-fold difference for MBC, MBN and MBC : SOC, respectively).

Seasonal effects on microbial biomass were few and inconsistent across locations. At Fargo, MBC was greater ($P = 0.0303$) in summer than in spring at 7.5–15 cm, while MBC at Mandan was greatest ($P = 0.0394$) in fall compared to spring and summer at the same depth. Seasonal trends in MBN at Fargo and Mandan were similar to MBC. Other locations exhibiting seasonal effects on MBN included Brookings (0–7.5 cm; greatest in spring; $P = 0.0080$), Bushland (0–7.5 cm; greatest in spring; $P = 0.0181$), and Mead (15–30 cm; greatest in fall; $P = 0.0421$).

Table 3. Mean values for microbial biomass C (MBC), microbial biomass N (MBN), MBC : SOC, and qCO_2 within conventional (CON) and alternative (ALT) treatments and perennial vegetation areas (Grass) in eight long-term cropping system experiments.

	Microbial biomass (kg ha^{-1})											
	Carbon			Nitrogen			MBC : SOC[1] (kg Mg^{-1})			qCO_2^{-1} (mg CO_2 mg^{-1} MBC day^{-1})		
Location/Soil depth (cm)	CON[2]	ALT	Grass	CON	ALT	Grass	CON	ALT	Grass	CON	ALT	Grass
Akron												
0–7.5	–[3]	177	–	29.7	31.8	–	–	23.3	–	0.077	0.162	–
7.5–15	114	134	–	15.8	15.8	–	19.3	21.1	–	0.057	0.053	–
15–30	203	254	–	28.1	29.7	–	16.7	20.1	–	0.124	0.050	–
Brookings												
0–7.5	331	375	–	34.6	40.4**	–	17.9	20.8	–	0.061	0.048	–
7.5–15	366	380	–	32.3	31.0	–	18.4	20.0	–	0.026	0.027	–
15–30	548	544	–	57.8	51.4	–	15.5	17.0	–	0.020	0.021	–
Bushland												
0–7.5	209	331	–	26.3	37.1***	–	20.9	25.4	–	0.084	0.066	–
7.5–15	197	223	–	20.3	24.6**	–	22.3	25.1	–	0.025	0.027	–
15–30	305	384	–	35.5	42.3**	–	19.5	24.1	–	0.030	0.073	–
Fargo												
0–7.5	243	491***	*645*	42.0	62.6**	*72.1*	13.2	20.8***	*21.8*	0.050	0.025	0.039
7.5–15	259	334	*634*	42.9	42.3	77.5	13.6	14.2	*28.8*	0.023	0.019	0.014
15–30	391	401	*787*	64.9	52.0	*92.8*	11.1	11.0	*19.0*	0.021	0.024	0.016
Mandan												
0–7.5	297	444**	*743*	30.9	49.2**	*90.6*	15.3	19.7	*24.1*	0.045	0.048	0.054
7.5–15	213	227**	*527*	16.8	30.1***	*45.1*	11.5	15.8**	*24.6*	0.023	0.024	0.026
15–30	275	453	*618*	23.5	36.5	*59.4*	10.6	13.6**	*21.0*	0.023	0.020	0.030
Mead												
0–7.5	195	324**	*812*	29.6	36.7	*100.9*	13.1	22.3***	*35.0*	0.072	0.062	0.056
7.5–15	237	272*	*352*	28.1	32.2**	*49.2*	17.0	20.8	*18.4*	0.040	0.031	0.042
15–30	317	284	*739*	37.2	31.5	*67.6*	15.7	16.5	*21.3*	0.027	0.034	0.024
Sidney												
0–7.5	–	154	*677*	24.3	27.6	*80.6*	–	11.4	*35.3*	–	–	0.063
7.5–15	208	193	*293*	21.8	17.4	*41.5*	19.4	21.2	*33.8*	0.047	0.053	0.036
15–30	263	211	*145*	26.1	20.0	*24.7*	18.9	19.7	*12.0*	0.052	0.058	0.075
Swift Current												
0–7.5	288	491**	–	32.8	45.2	–	16.5	23.1*	–	0.057	0.087	–
7.5–15	227	352**	–	23.3	35.6	–	13.3	18.6**	–	0.029	0.023	–
15–30	239	320**	–	26.1	45.1	–	12.7	15.2	–	0.035	0.026	–

[1] MBC : SOC, ratio of MBC to soil organic C; qCO_2, mg CO_2 respired mg^{-1} MBC day^{-1}.

[2] Sampling times: Fargo—peak biomass, 2000; Mandan—preplant, 2000; Mead—peak biomass, 2000; Sidney—preplant, peak biomass, and post-harvest, 2001 (average of three sampling times presented).

[3] –, not estimated.

*, **, ***, values between CON and ALT treatments within a property and soil depth significantly different at $P \leqslant 0.1$, 0.05, and 0.01, respectively.

Table 4. Summary of regression analysis for microbial biomass carbon (MBC) and nitrogen (MBN), potentially mineralizable N (PMN), water-stable aggregates (WSAs), and total glomalin (TG) using adjusted r^2 of variables defining management, climatic, and sampling factors.

	Model with maximum adjusted r^2			Best two-component model	
Parameter	**Adj r^2**	**Variables[1]**	**No. of variables**	**Adj r^2**	**Variables**
0–7.5 cm					
MBC	0.161	D, F, L, R, S, T	6	0.10	D, T
MBN	0.146	D, F, N, R, S, T	6	0.08	F, T
PMN	0.107	F, L, N, R, T, S	6	0.06	F, S
WSA	0.59	D, F, L, N, R, S, T	7	0.40	F, S
TG	0.42	D, L, N, R, S, T	6	0.18	S, T
7.5–15 cm					
MBC	0.305	F, N, R, T	4	0.30	F, T
MBN	0.431	F, L, N, R, S, T	6	0.31	L, N
PMN	0.227	F, L, N, S, T	5	0.16	F, S
15–30 cm					
MBC	0.227	D, F, N, R, S	5	0.18	F, T
MBN	0.223	D, F, L, N, R, T	6	0.13	F, T
PMN	0.126	D, F, R, S	4	0.08	S, T

[1] D, maximum tillage depth; F, presence (1) or absence (0) of fallow in the rotation; L, presence (1) or absence (0) of legume in the rotation; N, total number of species included in rotation cycle; R, mean annual precipitation; S, sampling time and year of sampling; T, mean annual temperature.

Levels of MBC and MBN at 7.5–15 cm were more responsive to management, climatic, and sampling factors than at 0–7.5 and 15–30 cm (Table 4). Specific factors most closely associated with MBC and MBN in two-component models included the presence or absence of fallow and mean annual temperature. Both frequency of fallow and mean annual temperature were negatively correlated with MBC and MBN at all three depth increments (data not shown). Fallow represents an extreme condition for microorganisms, dramatically limiting the amount of available nutrients for growth and activity[42], while temperature greatly influences decomposition rates in soil[43], thereby altering levels of nutrients to support microbial activity.

Potentially mineralizable N

Management affected PMN at Brookings, Bushland, Fargo, Mandan, and Mead, where the ALT treatment had 8.0, 14.3, 6.8, 13.9, and 10.2 kg ha^{-1} more PMN, respectively, than the CON treatment in the surface 7.5 cm (Table 3). These results are supported by a previous evaluation[11], where treatments with intensive crop sequences and/or reduced tillage had higher levels of PMN than treatments with monoculture crop sequences, fallow periods, and/or significant tillage. At Brookings and Mead, increased crop rotation diversity in the ALT treatment likely contributed to greater PMN at 0–7.5 cm, as both locations contrasted 4-year rotations with continuous corn. Increased cropping intensity (continuous winter wheat) in the ALT treatment was responsible for greater PMN at Bushland for all three depth increments. A combination of increased cropping intensity and reduced tillage at Mandan resulted in greater PMN in the surface 15 cm of the ALT treatment. Observations at Bushland and Mandan underscore the value of annual cropping and reduced tillage to enhance soil nutrient reserves in climatically extreme environments. At Fargo, surface accumulation of crop residue from the use of no-till resulted in greater PMN at 0–7.5 cm in the ALT treatment as compared to the CON treatment. An opposite trend was observed at 15–30 cm, where inversion of crop residue by moldboard plowing resulted in 2.3 kg ha^{-1} more PMN in the CON treatment.

There were two or three times more PMN in perennial vegetation areas at Fargo, Mandan, Mead, and Sidney than in the ALT treatment at 0–7.5 cm (Table 5). Differences in PMN between perennial vegetation areas and cropping systems can be a reflection of inherent soil fertility lost since conversion to production agriculture.

PMN did not differ between udic and ustic soil moisture regimes at 0–7.5 cm for the preplant sampling time ($P = 0.5658$; data not shown). Additionally, differences in PMN between ALT and CON treatments within moisture regimes were similar (10.9 and 9.8 kg ha^{-1} difference within udic and ustic moisture regimes, respectively). Results from regression analysis indicated management, climatic, and sampling factors were generally poor predictors of PMN (Table 4), as models with the maximum adjusted r^2 values were less than 0.25 at all three depth increments.

Sampling time had a significant effect on PMN at all locations, but only at Akron, Brookings, Bushland, and Mead was sampling time significant for more than one soil depth (data not shown). Trends in PMN over time were similar across all three depth increments at each location

Table 5. Mean values for potentially mineralizable N (PMN) within conventional (CON) and alternative (ALT) treatments and perennial vegetation areas in eight long-term cropping system experiments.

	PMN (kg ha^{-1})								
	0–7.5 cm			7.5–15 cm			15–30 cm		
Location	CON	ALT	Grass[1]	CON	ALT	Grass	CON	ALT	Grass
Akron	25.1	24.9	–[2]	9.1	10.0	–	23.0	14.6	–
Brookings	26.3	34.3**	–	17.8	17.4	–	21.5	21.5	–
Bushland	17.6	31.9***	–	8.0	10.4*	–	7.2	12.3**	–
Fargo	14.4	21.2**	*62.2*	11.7	10.1	*19.9*	12.9	10.6*	*15.2*
Mandan	21.7	35.6*	*67.1*	7.5	19.7***	*32.1*	9.0	15.7	*41.2*
Mead	19.3	29.5***	*70.9*	10.8	11.3	*23.6*	7.4	7.9	*19.8*
Sidney	20.3	20.4	*88.5*	8.5	13.0	*21.7*	6.3	10.8	*8.1*
Swift Current	23.7	45.8	–	14.2	22.6	–	12.5	15.1	–

[1] Grass, perennial vegetation area.
[2] –, not estimated.
*, **, ***, values between CON and ALT treatments within a property and soil depth are significantly different at $P \leqslant 0.1$, 0.05, and 0.01, respectively.

(data not shown), and were typically greatest within a year during the preplant sampling time, thereby providing an upper estimate of the capacity of the soil to supply plant-available N early in the growing season.

PMN and MBN are regarded as useful measures for assessing biologically active N reserves in soil. Assessment of PMN by anaerobic incubation, however, is considerably less involved and costly than MBN, and therefore the association between the two parameters is of interest to researchers. In this study, PMN was significantly correlated with MBN across locations and depths ($r = 0.31$; $P < 0.001$; $n = 1075$). A much stronger association between PMN and MBN was observed by Gajda et al.[11] at 0–7.5 cm ($r^2 = 0.841$). However, their evaluation was from one year (1998) with one sampling time (spring), which eliminated the temporal variability inherent to both parameters included in this study.

Aggregate stability and glomalin

Mean values for WSA and TG varied by location and treatment (Table 6). The lowest values for WSA were at Akron and Mandan (CON treatment) while the highest values occurred at Fargo (ALT treatment). TG ranged from about 1.7 to 5.5 mg g^{-1} across all locations, with lowest values at Akron and Sidney and highest values at Swift Current and Fargo. This range of values for TG was expected for cropped soils. TG values of 0.7–5.3 mg g^{-1} were found previously in experimental plots at Akron[15]. Soils at four sites in Corn Belt agro-ecosystems had TG from 0.7 to 3.8 mg g^{-1} and from 0.7 to 5.3 mg g^{-1} for CON tillage and no-tillage, respectively (S.F. Wright, unpublished data).

Management effects on WSA were observed at five of the eight locations (Table 6). The ALT treatment had greater WSA at four of the locations (Bushland, Fargo, Mandan, and Swift Current), with relative differences between treatments ranging from 13 to 133%. The CON treatment at Sidney, however, had greater WSA than the ALT treatment. Possible differences in sampling protocol at

Table 6. Means for water-stable aggregates (WSA) and total glomalin (TG) at 0–7.5 cm for conventional (CON) and alternative (ALT) treatments in eight long-term cropping system experiments.

Location/Treatment	TG (mg g^{-1})	WSA (g kg^{-1})
Akron		
CON	1.75	110
ALT	1.83	124
Brookings		
CON	2.61	491
ALT	2.58	495
Bushland		
CON	2.76	377***
ALT	2.96	456
Fargo		
CON	4.45	739**
ALT	5.46	832
Mandan		
CON	2.81**	218***
ALT	3.57	507
Mead		
CON	3.28	584
ALT	2.65	622
Sidney		
CON	2.67*	486***
ALT	2.23	360
Swift Current		
CON	4.72	485***
ALT	5.12	609

*, **, ***, difference between CON and ALT treatments significant at $P \leqslant 0.1$, 0.05, and 0.01, respectively.

Sidney may be a contributing factor to the contrary trend in WSA between treatments (as discussed by Wienhold et al.[19]). In this study, TG differed between treatments only at Mandan, where the ALT treatment (continuous cropping with no-tillage) had 27% more TG than the CON treatment (crop–fallow with CON tillage) ($P < 0.05$).

Sampling time had a significant effect on WSA and TG at all locations, except for WSA at Swift Current (data not shown). Temporal fluctuations in WSA corresponded to those for TG except at Swift Current, where a precipitous decrease in TG during the 2000 growing season was not associated with a decrease in WSA. Locations with fallow in the rotation (Bushland and Mandan) had lower values for TG and WSA during the fallow period (data not shown).

WSA was affected more by management and sampling time than by climatic factors. The best two-component model for WSA (adjusted $r^2 = 0.40$) included presence or absence of fallow (F) and sampling time (S) (Table 4). The best model (adjusted $r^2 = 0.59$) included all variables. Pearson product moment correlations for WSA with the above variables showed a negative correlation with F and positive correlations with presence or absence of a legume (L), mean annual precipitation (R), S, and the number of species in the rotation (N) ($P < 0.001$; data not shown). The best two-component model for TG was S and the mean annual temperature (T) (adjusted $r^2 = 0.18$). The best model included all of the variables except F. Correlations for TG with the variables tested for regression models were positive for L and negative for R, S, T, and the maximum tillage depth (D) ($P \leqslant 0.05$; data not shown).

There were significant positive correlations between WSA and clay ($r = 0.61$, $P < 0.001$, and $n = 291$) and WSA and TG ($r = 0.43$, $P < 0.001$, and $n = 294$). Previous work by Kemper and Koch[44] has shown organic matter, clay, and iron oxide to account for 44% of the variance in WSA in western soils. More recent work indicates that glomalin, a fraction of SOM, is a major factor in aggregate stability[15,45]. Using the current data for the mean values for each plot, multiple regression of WSA with the variables SOM, clay, TG, and Fe resulted in the following equations ($n = 45$ and $P < 0.05$):

$$\text{WSA} = 6.39 + 14.65\ \text{SOM}\ (r^2 = 0.56), \quad (1)$$

$$\text{WSA} = -1.69 + 0.80\ \text{clay} + 9.66\ \text{SOM}\ (r^2 = 0.66), \quad (2)$$

$$\text{WSA} = -8.12 + 0.84\ \text{clay} + 4.48\ \text{SOM} + 6.22\ \text{TG}\ (r^2 = 0.72), \quad (3)$$

$$\text{WSA} = -7.66 + 1.00\ \text{clay} + 8.58\ \text{TG}\ (r^2 = 0.70) \quad (4)$$

and the following stepwise model,

$$\text{WSA} = -17.1 + 1.35\ \text{clay} + 0.23\ \text{Fe} + 6.27\ \text{TG}\ (r^2 = 0.73, \text{adjusted}\ r^2 = 0.70). \quad (5)$$

These results indicated that measures of innate soil factors—clay and Fe—and glomalin accounted for 70% of the variability in WSA. Across locations, clay content was highest at Fargo (480 g kg^{-1}), Mead (375 g kg^{-1}), and Bushland (315 g kg^{-1}), corresponding to three locations with high WSA. An exception to the positive association between clay and WSA was at Swift Current, where WSA was high for the ALT treatment, but clay content was relatively low for the soils examined (*c.* 235 g kg^{-1}). However, TG at Swift Current was high, indicating that clay and TG may be important for aggregate stability in this soil.

FAME profiles

FAME profiles were primarily of bacterial origin (Table 2). Gram-positive (iso- and anteiso-FAMEs) and Gram-negative (hydroxyl and cyclo-FAMEs) bacteria were present in principal component (PC) 1, 2, and 3, while fungi (polyunsaturated C_{18} FAME) were present in PC 2 only. FAME profiles were highly dependent on location (Fig. 1a). Given the geographical breadth of the study, differences in climate, soil type, and management practices contributed to differences in the flora and fauna creating FAME profiles. Among factors contributing to FAME profiles, sampling depth had significant effects on PC 1, 2, and/or 3 at all locations (data not shown). The effect of depth is shown in Figure 1b, where distinctly different outcomes for PC 1 and 2 were observed across depths at Akron and Mead, locations representative of the ustic and udic soil moisture regimes, respectively. Locations where FAME profiles were analyzed for more than one sampling time yielded significant time effects (Fig. 1c), presumably due to shifts in populations of flora and fauna in response to fluctuations in weather. These findings corroborate with previous evaluations[46,47], where soil type, soil depth, and sampling time have been identified as having an overriding influence on FAME profiles.

Four locations—Brookings, Bushland, Mead, and Swift Current—had significant differences between treatments in PC 1 or 2 (Fig. 1d). At three of these sites—Bushland, Mead, and Swift Current—ALT treatments scored higher in PC 1 and/or 2 than CON treatments, indicating similar community shifts due to alternative management in these soils. At Akron (0–7.5 cm), Bushland (7.5–15 cm), Mandan (0–7.5 and 7.5–15 cm), and Swift Current (0–7.5 and 15–30 cm), the ALT treatment had greater total FAME than the CON treatment, indicating larger overall soil biomass (Table 7). Differences between treatments were most pronounced at Mandan, where total FAME in the ALT treatment was nearly double of that observed within the CON treatment. Unlike other locations, total extracted FAME at Sidney was greater within the CON treatment than the ALT treatment, corresponding to a similar trend between treatments observed for TG and aggregate stability.

Consistent trends between treatments in individual FAME biomarkers for bacteria, fungi, and protozoa were not common across locations, indicating a strong site-specific effect on soil biota composition. Only one location

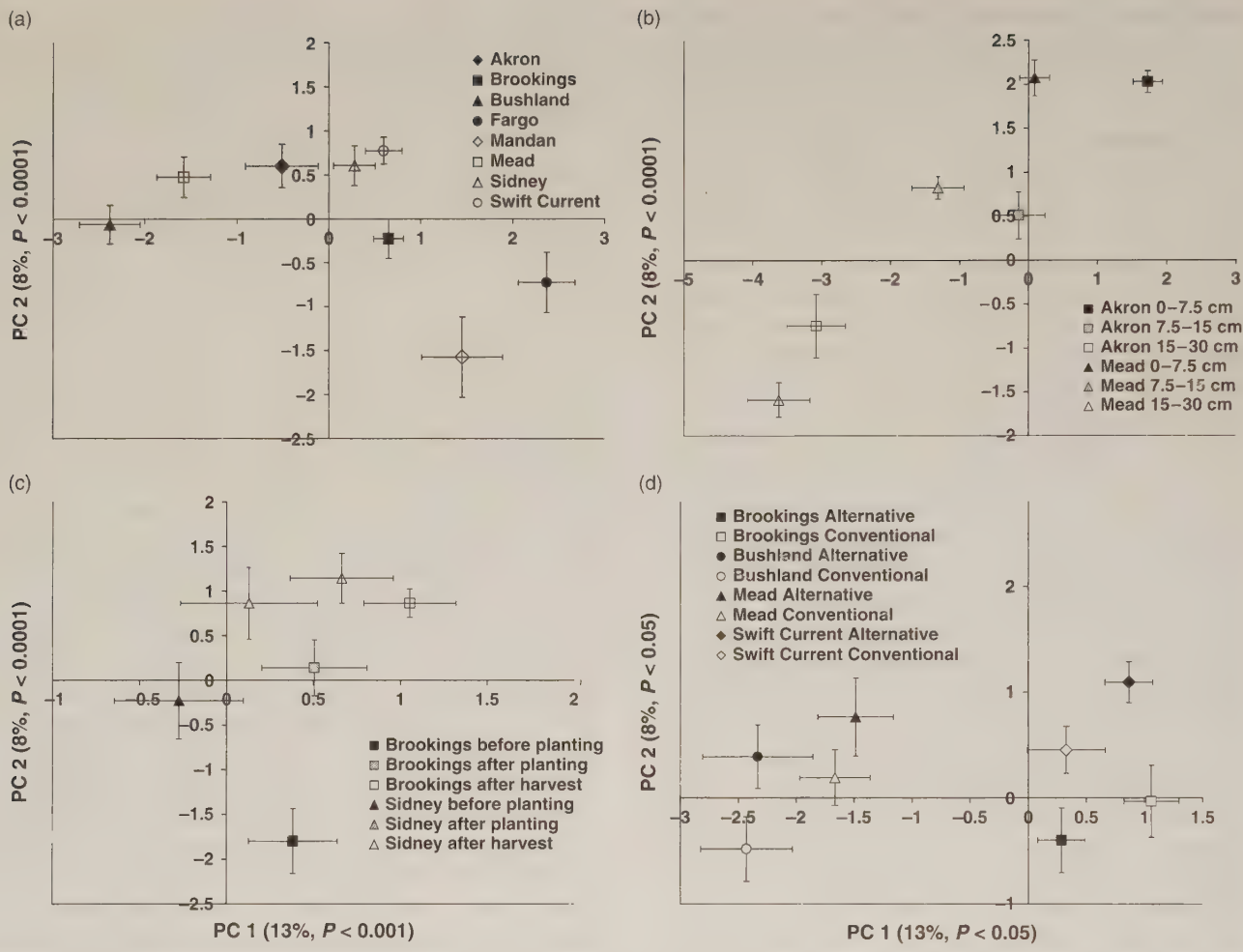

Figure 1. (a) Principal components analysis (PCA) of Fatty acid methyl ester (FAME) profiles across all locations in 2000. Data shown are the means by location, ± SEM. (b) PCA of FAME profiles across depths for Akron and Mead in 2000. Data shown are the means by location and depth, ± SEM. (c) PCA of FAME profiles across sampling times for Brookings and Sidney in 2000. Data shown are the means by location and sampling time, ± SEM. (d) PCA of FAME profiles of conventional and alternative treatments at several sites. Data shown are the means by location and treatment, ± SEM.

(Mandan) exhibited a significant treatment effect on Gram-negative bacteria, with a greater percentage observed in the ALT treatment at 0–7.5 cm. At Bushland and Swift Current, a greater proportion of Gram-positive bacteria was observed in CON treatment than ALT treatment at 7.5–15 or 15–30 cm, yet the opposite was observed at Sidney for the same depths (Table 7). Ratios of bacterial to fungal biomarkers increased with depth at all locations except Swift Current, indicating soils at most locations were increasingly bacteria-dominated at deeper soil depths. Within individual locations, the biomarker for fungal cells, namely polyunsaturated C_{18} FAME, was greater in ALT than CON treatments at Bushland (0–7.5 and 7.5–15 cm), Fargo (15–30 cm), and Sidney (0–7.5 cm) (Table 7).

The biomarker for protozoa, polyunsaturated C_{20} FAME[32], made up less than 1% of the proportion of total FAME at each location (Table 7). In spite of its relative scarcity, differences between treatments for the biomarker were observed at Akron (0–7.5 cm), Brookings (7.5–15 cm), and Bushland (15–30 cm). In each case, the ALT treatment had a higher percentage of protozoa biomarkers than the CON treatment, making it the only biomarker to respond consistently across locations with respect to trends between treatments. This finding is consistent with previous research by Schutter et al.[48], where greater amounts of fungal and protozoan FAME biomarkers were observed in alternatively managed soils (as reflected by cover crop usage) relative to soils fallowed over winter.

Summary and Conclusions

Cropping system effects on soil biological characteristics in this study generally followed expected trends based on results from previous evaluations in the Great Plains[11,14,15,49]. ALT cropping systems had greater MBC, MBN, and PMN than CON cropping systems in at least one-half of the locations included in this study. WSAs, an important biophysical indicator of soil condition, were greater in ALT than CON treatments at four locations.

Table 7. Mean values for FAME profile parameters at three depths for conventional (CON) and alternative (ALT) treatments in eight long-term cropping system experiments in 1999–2000.

	0–7.5 cm		7.5–15 cm		15–30 cm	
Parameter	**CON**	**ALT**	**CON**	**ALT**	**CON**	**ALT**
Akron						
Total FAME (nmol g^{-1})	21.8	34.4*	23.9	18.9	19.1	15.0
Hydroxy FAME[1] (%)	3.01	3.20	3.73	2.56	3.18	2.38
Iso-FAME + anteiso-FAME (%)	23.0	22.1	21.9	19.3	18.3	17.5
Polyunsat. C_{18} FAME (%)	10.19	9.05	6.49	6.76	3.70	6.16
Bacterial/fungal markers	2.56	2.79	3.95	3.23	5.80	3.23
Polyunsat. C_{20} FAME (%)	0.031	0.109*	0.025	0.112	0.032	0.102
Brookings						
Total FAME (nmol g^{-1})	63.6	75.8	55.5	58.7	38.9	46.1
Hydroxy FAME (%)	2.92	2.53	3.12	2.41	3.27	3.25
Iso-FAME + anteiso-FAME (%)	23.7	22.9	23.0	23.2	23.3	23.9
Polyunsat. C_{18} FAME (%)	9.34	9.15	7.83	7.14	6.52	6.04
Bacterial/fungal markers	2.85	2.78	3.33	3.59	4.08	4.49
Polyunsat. C_{20} FAME (%)	0.247	0.187	0.160	0.286*	0.125	0.198
Bushland						
Total FAME (nmol g^{-1})	55.0	64.0	36.2	65.4**	45.2	62.7
Hydroxy FAME (%)	2.35	2.74	1.84	1.50	1.21	1.38
Iso-FAME + anteiso-FAME (%)	21.0	22.0	19.9	16.8**	19.2	16.8*
Polyunsat. C_{18} FAME (%)	6.77	7.71*	3.15	4.01*	2.69	1.96**
Bacterial/fungal markers	3.45	3.21	6.91	4.56**	7.60	9.27
Polyunsat. C_{20} FAME (%)	0.028	0.049	0.076	0.107	0.018	0.151*
Fargo						
Total FAME (nmol g^{-1})	34.2	20.4	28.4	29.3	9.1	15.7
Hydroxy FAME (%)	2.33	1.70	5.13	2.31	2.68	3.14
Iso-FAME + anteiso-FAME (%)	28.3	25.4	27.9	24.7	30.7	26.2
Polyunsat. C_{18} FAME (%)	12.47	4.56	5.10	9.41	1.32	4.56**
Bacterial/fungal markers	2.46	5.96	6.48	2.87	25.25	6.44
Polyunsat. C_{20} FAME (%)	0	0.296	0	0.299	0.183	0
Mandan						
Total FAME (nmol g^{-1})	87.9	170.5**	53.0	104.1**	37.9	48.1
Hydroxy FAME (%)	2.65	3.82*	3.18	3.06	2.19	2.09
Iso-FAME + anteiso-FAME (%)	25.8	23.9	25.9	24.2	26.3	25.7
Polyunsat. C_{18} FAME (%)	6.40	6.96	3.98	4.35	3.96	4.07
Bacterial/fungal markers	4.44	4.00	7.37	6.32	7.75	6.84
Polyunsat. C_{20} FAME (%)	0.242	0.331	0.272	0.196	0.087	0.143
Mead						
Total FAME (nmol g^{-1})	57.9	68.4	30.6	34.0	31.0	24.6
Hydroxy FAME (%)	2.75	2.75	2.46	2.52	1.10	0.84
Iso-FAME + anteiso-FAME (%)	19.0	20.8	20.4	20.8	20.8	21.9
Polyunsat. C_{18} FAME (%)	10.98	11.09	5.86	6.74	3.48	3.57
Bacterial/fungal markers	1.98	2.12	3.91	3.46	6.29	6.37
Polyunsat. C_{20} FAME (%)	0.225	0.223	0.207	0.184	0.186	0.162
Sidney						
Total FAME (nmol g^{-1})	111.0	78.7**	46.8	37.1	30.3	23.8
Hydroxy FAME (%)	4.04	3.07	3.62	3.08	3.53	2.76
Iso-FAME + anteiso-FAME (%)	20.0	20.7	20.2	22.8*	18.5	23.5*
Polyunsat. C_{18} FAME (%)	11.88	15.00**	6.13	7.43	5.36	5.88
Bacterial/fungal markers	2.02	1.58**	3.88	3.48	4.11	4.46
Polyunsat. C_{20} FAME (%)	0.391	0.419	0.347	0.288	0.192	0.206
Swift Current						
Total FAME (nmol g^{-1})	40.2	73.7*	36.0	43.3	11.3	29.3**
Hydroxy FAME (%)	5.65	4.48	5.25	5.48	2.85	3.56
Iso-FAME + anteiso-FAME (%)	23.1	23.4	23.5	20.4*	21.8	21.8
Polyunsat. C_{18} FAME (%)	7.83	7.91	6.83	6.93	7.83	9.11
Bacterial/fungal markers	3.67	3.52	4.21	3.73	3.15	2.78
Polyunsat. C_{20} FAME (%)	0	0.074	0	0.077	0.054	0

[1] Biomarkers for microbial groups: hydroxy FAME, Gram-negative bacteria; iso-FAME + anteiso-FAME, Gram-positive bacteria; polyunsat. C_{18} FAME, fungi; polyunsaturated C_{20} FAME, protozoa[33,34].

*, **, Difference between CON and ALT treatments within a depth significant at $P \leqslant 0.05$ and 0.01, respectively.

However, differences in WSA between treatments did not necessarily translate to greater TG in ALT systems, as only one location (Mandan) had a significant difference in TG between treatments. FAME profiles varied greatly across locations, with few consistent differences between treatments. However, ALT treatments tended to have a more abundant soil biomass than CON treatments, as indicated by greater total extracted FAME.

Management factors controlling trends in soil biological properties between cropping systems included crop diversity, degree of soil disturbance by tillage, and presence/absence of fallow. Among the three factors, greater crop diversity—as shown through the continuous corn/4-year rotation contrasts at Brookings and Mead—resulted in greater levels of MBN and PMN in the surface 7.5 cm of the ALT treatment. Blocking locations by degree of soil disturbance or presence/absence of fallow did not yield consistent results across locations. Furthermore, even when two management factors were present at a location—such as at Akron, Mandan, and Sidney—the resulting trends in soil biological properties between cropping systems were not consistent. Such findings imply that generalizations regarding tillage and fallow effects on soil biological properties in the Great Plains cannot be made without considering site-specific attributes, such as spatial and temporal variability of soil properties and 'time in treatment' within a location.

All soil biological properties assessed in this study varied over time. This result was expected, as biological parameters are directly affected by weather-related factors such as temperature and moisture, and indirectly affected by plants through fluctuations in nutrients and carbon inputs. Consequently, no single sampling time can be recommended as being most appropriate for assessing the status of all soil biological properties. However, certain 'common sense' considerations apply, such as sampling when the climate is most stable and when there have been no recent soil disturbances[50]. When considering the three sampling times in this study (preplant, peak biomass, and post-harvest), the first and last times qualify by these criteria.

The amount of time necessary to detect changes in soil biological properties is a function of organic matter inputs to the soil, which, in turn, are largely dependent on climatic and edaphic factors dictating production potential[6]. The ability to detect changes, however, is also affected by the sampling scheme employed by the investigator. Selection of sampling depths, in particular, has a significant effect on whether changes in soil condition are observed. Sampling depths that are too large run the risk of diluting changes occurring at a particular depth increment in the soil profile. Conversely, smaller depth increments increase the potential for detecting change, but increase sampling and analysis demands, thereby rendering them impractical for most studies. In this study, most treatment effects were concentrated in the surface 0–15 cm, underscoring the importance of sampling to at least this depth in future studies. Partitioning the surface 15 cm into different depth increments (e.g., 0–5 and 5–15 cm) may be advisable in order to better quantify near-surface effects of management. Such a sampling scheme would offer advantages for detecting soil changes in regions where production levels are low or where management practices have been in place for less than 10 years.

In its simplest form, soil quality refers to the capacity of soil to function[51]. Soil functions vary by land use, but are generally regarded to include (1) water and solute retention and flow, (2) physical stability and support, (3) retention and cycling of nutrients, (4) buffering and filtering of potentially toxic materials, and (5) maintenance of biodiversity and habitat[52]. Based on the status of soil biological properties assessed in this study, it appears that ALT treatments at most of the locations enhanced functions 3 and 5, implying improved agro-ecosystem performance over time.

Temporal variation in soil biological properties in this study underscored the importance of interpreting results in the context of treatment and weather-related attributes unique to the time the soil samples are collected. Trends in soil biological properties over time occasionally could be explained based on knowledge of management impacts and weather conditions at a particular location. However, much variation defied a straightforward explanation. It is perhaps this issue that demands greater emphasis in future investigations of soil biological properties in Great Plains cropping systems. An improved understanding of seasonal patterns of microbial dynamics—along with effects on critical soil functions—could lead to greater production efficiencies, thereby enhancing agricultural sustainability within this climatically extreme region.

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Cropping system effects on soil quality in the Great Plains: Synthesis from a regional project

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Abstract

Soils perform a number of essential functions affecting management goals. Soil functions were assessed by measuring physical, chemical, and biological properties in a regional assessment of conventional (CON) and alternative (ALT) management practices at eight sites within the Great Plains. The results, reported in accompanying papers, provide excellent data for assessing how management practices collectively affect agronomic and environmental soil functions that benefit both farmers and society. Our objective was to use the regional data as an input for two new assessment tools to evaluate their potential and sensitivity for detecting differences (aggradation or degradation) in management systems. The soil management assessment framework (SMAF) and the agro-ecosystem performance assessment tool (AEPAT) were used to score individual soil properties at each location relative to expected conditions based on inherent soil-forming factors and to compute index values that provide an overall assessment of the agronomic and environmental impact of the CON and ALT practices. SMAF index values were positively correlated with grain yield (an agronomic function) and total organic matter (an agronomic and environmental function). They were negatively correlated with soil nitrate concentration at harvest (an indicator of environmental function). There was general agreement between the two assessment tools when used to compare management practices. Users can measure a small number of soil properties and use one of these tools to easily assess the effectiveness of soil management practices. A higher score in either tool identifies more environmentally and agronomically sustainable management. Temporal variability in measured indicators makes dynamic assessments of management practices essential. Water-filled pore space, aggregate stability, particulate organic matter, and microbial biomass were sensitive to management and should be included in studies aimed at improving soil management. Reductions in both tillage and fallow combined with crop rotation has resulted in improved soil function (e.g., nutrient cycling, organic C content, and productivity) throughout the Great Plains.

Key words: cropping systems, soil quality, crop rotation, tillage management, assessment tools

Introduction

Soils perform numerous functions in support of agro-ecosystems. They provide a substrate for supporting plant growth, a reservoir for many nutrients essential for plant growth, a filter maintaining air quality through interactions with the atmosphere, a storage and purification medium for water as it passes through the soil, and a site for biological activity involved in the decomposition and recycling of

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animal and plant products. Failure to recognize the interdependence of the soil functions has led to implementation of practices that have impaired many of these functions[1]. As soil degradation (e.g., compaction, loss of organic matter, and acidification) became apparent, management practices were developed to maintain or improve soil functions. Characteristics of improved management systems in the Great Plains included reduced incidence of fallow, reduced tillage intensity, and increased crop diversity[2]. In the Great Plains, soil properties typically change slowly because low moisture limits the rates of chemical and biological processes[3], plant productivity, and associated organic matter additions. These conditions make monitoring soil change a challenge.

In spite of the assessment challenges, land managers need easily measured indicators and assessment methods for determining how their management is affecting soil functions. To make such assessments, physical, chemical, and biological soil properties are often selected as part of a minimum data set[4]. Assessment of soil functions requires appropriate choices regarding time of year to sample, soil properties to measure, and interpretations to make. Conflicting results exhibited by individual soil attributes often further complicate the assessment of management effects on soil quality[5]. Larson and Pierce[6] suggested that dynamic assessments were needed to determine temporal variation in attributes and to identify trends in management effects. Combining a variety of soil attributes into an index can partially resolve conflicting results and assist in assessing management effects[7]. In 1999, the Great Plains Cropping System Network began to address a number of these issues by investigating existing long-term cropping system experiments throughout the region.

The original objectives for this regional study were:

(1) to quantify the temporal dynamics exhibited by selected physical, chemical, and biological attributes in the upper 30 cm of soil;
(2) to compare selected physical, chemical, and biological soil quality attributes between contrasting management practices [e.g., conventional (CON) tillage, fallow, and monocropping versus conservation tillage, intensive cropping, and crop rotation] in the Great Plains and Western Corn Belt; and
(3) to assess recently developed methods for their potential to quantify soil quality attributes that may be sensitive to management.

The purpose of this summary paper is to evaluate, using the regional data, two new assessment tools, the soil management assessment framework (SMAF) and the agro-ecosystem performance assessment tool (AEPAT), to aid in interpreting the impact management systems have on soil properties and functions.

Materials and Methods

Contrasting management systems were selected for sampling at eight research sites throughout the Great Plains (Table 1)[8]. Composite soil samples were collected from the 0–15 cm depth three times each year. Further details of the study sites and soil sampling protocol[8], and methods for measuring physical[9], chemical[10], and biological[11] soil properties used in the study can be found in the accompanying papers. Two recently developed assessment tools were used to aid in interpretation of the large data set generated by this study: the SMAF[12] and the AEPAT[13].

Table 1. Contrasting management treatments within eight long-term cropping systems. Treatments selected at each site differed in management intensity as characterized by either type or frequency of tillage, cropping intensity, and/or crop rotation diversity and are termed conventional (CON) or alternative (ALT).

Location/soil series	Treatment	Crop sequence	Tillage	N rate[1]
Akron, CO	CON	WW–F[2]	Sweep (fallow)	Varied
Weld silt loam	ALT	WW–C–M	No tillage	Varied
Brookings SD	CON	C–C	Chisel plow and disk	High
Barnes sandy clay loam	ALT	C–SB–SW–A	Chisel plow and disk	0
Bushland, TX	CON	WW–SO–F	No tillage	Varied
Pullman silty clay loam	ALT	WW–WW	No tillage	0
Fargo, ND	CON	DW–P	Fall plow	0
Fargo silty clay	ALT	DW–P	No tillage	0
Mandan, ND	CON	SW–F	Chisel plow and disk	Medium
Wilton silt loam	ALT	SW–WW–SU	No tillage	Medium
Mead, NE	CON	C–C	Tandem disk, 2×	High
Sharpsburg silty clay loam	ALT	C–SB–SO–OCL	Tandem disk, 2×	High
Sidney, MT	CON	SW–F	Tandem disk	45 kg ha^{-1}
Vida loam	ALT	SW–SW	No tillage	45 kg ha^{-1}
Swift Current, SK	CON	SW–F	Chisel plow and harrow	Varied
Swinton silt loam	ALT	SW–L	Chisel plow and harrow	Varied

[1] Varied = N fertilizer application rate based on soil test results.
[2] Abbreviations: A = alfalfa, C = corn, DW = durum spring wheat, F = summer fallow, L = lentil, M = proso millet, OCL = oat + clover, P = field pea, SB = soybean, SO = sorghum, SU = sunflower, SW = spring wheat, WW = winter wheat.

SMAF is an additive, non-linear indexing tool for assessing soil function[12]. Soil indicator values for the 0–7.5 cm and 7.5–15 cm depths were averaged and converted to index values using scoring curves that relate soil indicators to essential functions performed by soils. Scoring curves take the general forms of less is better (e.g., bulk density), more is better (e.g., organic C), or a local optimum (e.g., pH). The tool changes the scoring curves' inflection points and thresholds to account for differences in expected ranges due to inherent soil properties, climate, and crops. Scoring curves available in the most recent version of SMAF and measured at all sites in this study included physical (macro-aggregate percentage and bulk density), chemical [total organic C, electrical conductivity (EC), and pH], and biological [microbial biomass C, microbial quotient (relationship between microbial biomass C and mineralizable C), and potentially mineralizable N] soil properties. These soil properties are indicators of soil functions (e.g., nutrient reservoir and substrate for plant growth) related to agronomic production. Indicator scores were summed to generate an index value. Increasing index values denote increasing levels of soil function. We hypothesized that greater index values were associated with increased agronomic yield.

The CON and alternative (ALT) management systems at each location were compared using the calculated SMAF index values for each replication of both treatments at each sampling date. Analysis of variance was used to detect treatment, sampling time, and treatment × sampling time effects on index values. Effects were considered significant at $P < 0.10$. Correlation between SMAF index values and agronomic (grain yield) and environmental goals (nitrate concentration and organic matter content) were also calculated to determine the utility of using this index to assess management goals.

AEPAT is a performance-based assessment tool that utilizes user-selected scoring curves and weights to generate index values[13]. Measured indicators are assigned to agro-ecosystem functions. Weights are given to individual indicators based on the user's perception of the influence that indicator has on the assigned agro-ecosystem function. Weighted indicator scores are combined to generate an agro-ecosystem function score. Weights are also given to the agro-ecosystem functions based on the user's perception of the influence the functions have on agro-ecosystem sustainability. Weighted agro-ecosystem function scores are combined to generate a score for comparing management practices. To compare CON to ALT management at each site, food production and nutrient cycling functions were used to generate an AEPAT score:

$$\text{AEPAT score} = (\text{food production} \times W_{fp}) + (\text{nutrient cycling} \times W_{nc}) \quad (1)$$

For the AEPAT assessment, the food production function was assigned a weight (W_{fp}) of 75% and the nutrient cycling function a weight (W_{nc}) of 25% to reflect the importance of productivity and uncertainty of nutrient cycling to most land managers. Soil pH and spring nitrate-N concentration were the indicators assigned to the food production function. Soil pH was assigned a weight of 40% and spring nitrate-N a weight of 60%. Spring nitrate-N was assigned a slightly higher weight since N is the fertilizer nutrient most commonly limiting crop production in the Great Plains. Soil pH was included in the scoring function because pH serves as a sensitive indicator for inefficient N fertilizer use and pH values outside the optimum range strongly influence plant availability of several essential nutrients. A threshold value sigmoidal scoring curve was selected for the soil pH indicator with an optimal value of 6.5 in wheat (*Triticum aestivum* L.)-based systems and 6.3 in corn (*Zea mays* L.)-based systems. A higher is better logistic scoring curve was selected for the spring nitrate-N scoring curve with an optimal value of 200 kg ha^{-1} and a lower bound of 1 kg ha^{-1}.

Fall nitrate-N and organic C were selected as indicators for the nutrient cycling function to reflect the environmental importance of nitrate-N leaching losses and the agronomic importance of organic matter in nutrient cycling and soil structure in these systems. Fall nitrate-N and organic C were weighted equally at 50% for assessments at Fargo, Brookings, and Mead. Equal weights were assigned due to the need to maintain organic C and to minimize fall nitrate-N concentration to reduce the potential for leaching losses at these sites. Fall nitrate-N was assigned a weight of 25% at the other locations because of the reduced potential for leaching at these semi-arid sites. Organic C was assigned a weight of 75% to reflect the importance of organic matter in nutrient cycling and soil structure in these systems. A lower is better exponential scoring curve with an optimal value of 1 kg ha^{-1} and an upper bound of 200 kg ha^{-1} was selected for the soil fall nitrate-N indicator. A higher is better logistic curve with an optimal value of 110 Mg ha^{-1} and a lower bound of 20 Mg ha^{-1} was selected for the organic C scoring curve.

Comparisons of food production function, nutrient cycling function, and AEPAT scores for contrasting management practices at each location were performed using scores calculated for each year and each replication. Analysis of variance was used to determine differences among index values between treatments and among years for each location. Differences were considered significant at $P < 0.10$.

Results and Discussion

SMAF index values

Differences between treatments for SMAF index values were observed at Fargo, Mandan, Mead, and Swift Current (Table 2). At these four locations, SMAF index values (Fig. 1) for the ALT treatment were greater than those for the CON treatment. At Fargo, Mandan, Mead, and Sidney,

Table 2. *P*-values for main effects and interactions for soil management assessment framework (SMAF) index values for eight sites in the Great Plains.

	Location							
Effect	**Akron**	**Brookings**	**Bushland**	**Fargo**	**Mandan**	**Mead**	**Sidney**	**Swift Current**
	P-value							
Tmt	0.40	0.19	0.14	0.09	0.02	0.08	0.42	0.08
Time	0.01	< 0.01	< 0.01	< 0.01	0.09	< 0.01	0.23	0.19
Tmt × time	0.03	0.93	0.80	0.73	0.29	0.04	0.73	0.99

Tmt, treatment.

the SMAF index value for the grassed relic areas were greater than for the cropped treatments (but significantly so only at Mead and Sidney). The lower index scores for cropped treatments at Fargo and Mead likely reflect a decline in soil quality due to conversion of perennial vegetation to annual cropping and tillage[14]. The lower index scores for cropped treatments at Mandan and Sidney reflect the detrimental effect several decades of crop–fallow had on soil quality at these sites[15]. Greater index values for the ALT treatment than the CON treatment at Mandan and Swift Current reflect the improvement in soil quality when tillage intensity and the incidence of fallow were reduced at these sites[16–18].

Temporal variation in SMAF index values was observed at Akron, Brookings, Bushland, Fargo, Mandan, and Mead. At Akron and Mead, SMAF index values exhibited a treatment by time interaction (Table 2). At Akron, index values were similar at the first sampling and increased during the first year (sample times 1 and 2) when plots in both the treatments were in wheat (Fig. 2). From sampling

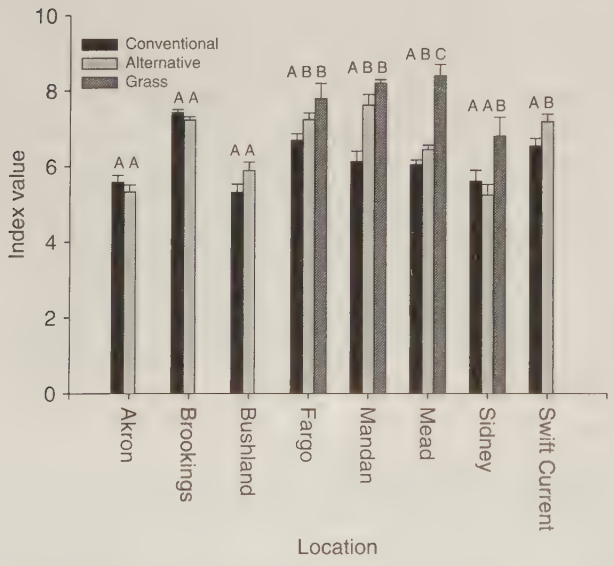

Figure 1. Soil management assessment framework (SMAF) index values (averaged across sampling times) for conventional, alternative, and grass plots at eight locations in the Great Plains. Error bar represents 1 SEM. Bars within a group having different letters above them are different at $P < 0.10$.

time four to five, when plots in the CON treatment were in fallow and plots in the ALT treatment were in corn, index values for the CON treatment decreased while those in the ALT treatment increased. Temporal variability exhibited by index values at Brookings, Bushland, and Fargo was likely due to weather effects on soil sampling variability, crop growth, and soil biological processes. Index values for both treatments exhibit temporal variation at Mandan with index values for the CON treatment being less than those for the ALT treatment at all sampling times. Temporal variability at Mandan is likely due to weather variation with the lower index values in the CON treatment reflecting the detrimental effect of fallow every other year (Fig. 2). At Mead, the temporal variability exhibited by the CON treatment likely reflects weather differences as this treatment was managed the same all 4 years (Table 1). In addition, a treatment by time interaction resulted from higher index values for the ALT treatment in years one (sample times 1, 2 and 3) and four (sample times 10, 11 and 12) but similar index values for the two treatments during the other sampling times (Fig. 2). Previous crop may explain the interaction exhibited at Mead: during year one the higher index values in the ALT treatment are probably a response to the oats (*Avena sativa* L.) and clover (*Trifolium pratense* L.) crop of the previous year. During year two, similar index values for the two treatments reflect the corn crop grown in each treatment. During year three, index values were maintained in the ALT treatments, which were planted to soybean (*Glycine max* L.) the previous year while index values in the CON treatment declined. In year four, index values exhibited similar temporal changes with values in the ALT treatment being greater at all sampling times than those of the CON treatment.

There was a correlation between SMAF index values and yield for the Mandan and Swift Current locations (Table 3). At both of these locations, the correlation was positive (Fig. 3). A positive correlation between SMAF index values and yield implies that the index may have utility for assessing the agronomic goal of soil management. Management resulting in increasing SMAF index values should result in increasing crop performance. Measuring a small set of soil indicators and using SMAF to assess management may allow producers to identify practices

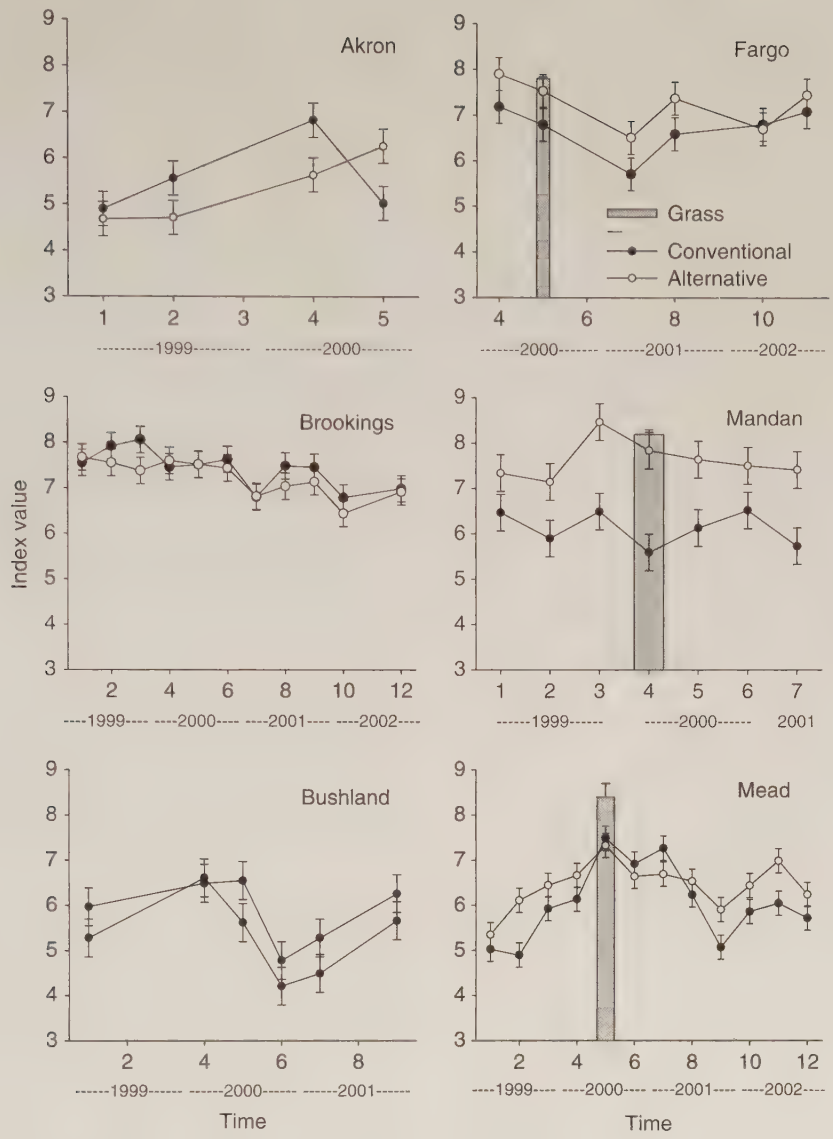

Figure 2. Soil management assessment framework (SMAF) index values as a function of time for six locations in the Great Plains. Error bars represent ±1 SEM. Sampling times correspond to preplant = 1, 4, 7, and 10; peak biomass = 2, 5, 8, and 11; post-harvest = 3, 6, 9, and 12.

Table 3. Correlation between soil management assessment framework (SMAF) index values and indicators of agronomic and environmental soil functions.

Location	Yield[1]	Nitrate-N[2]	Total Organic C[3]
Akron, CO	0.21 (0.687)[4]	0.15 (0.775)	−0.14 (0.793)
Brookings, SD	−0.63 (0.179)	0.85 (0.033)	0.01 (0.985)
Bushland, TX	n.d.	−0.94 (0.005)	−0.10 (0.853)
Fargo, ND	0.32 (0.533)	−0.61 (0.082)	0.70 (0.035)
Mandan, ND	0.89 (0.017)	−0.24 (0.537)	0.97 (< 0.001)
Mead, NE	−0.27 (0.607)	−0.89 (0.002)	0.86 (0.003)
Sidney, MT	−0.41 (0.421)	−0.91 (0.001)	0.07 (0.862)
Swift Current, SK	0.79 (0.061)	−0.28 (0.595)	0.74 (0.091)

[1] Correlation between index values averaged across sample times within a year and annual yield.
[2] Correlation between index value and nitrate-N concentration at planting.
[3] Correlation between index values and total organic C content averaged across sampling times within a year.
[4] Values in parenthesis are *P*-levels for the correlation analysis.

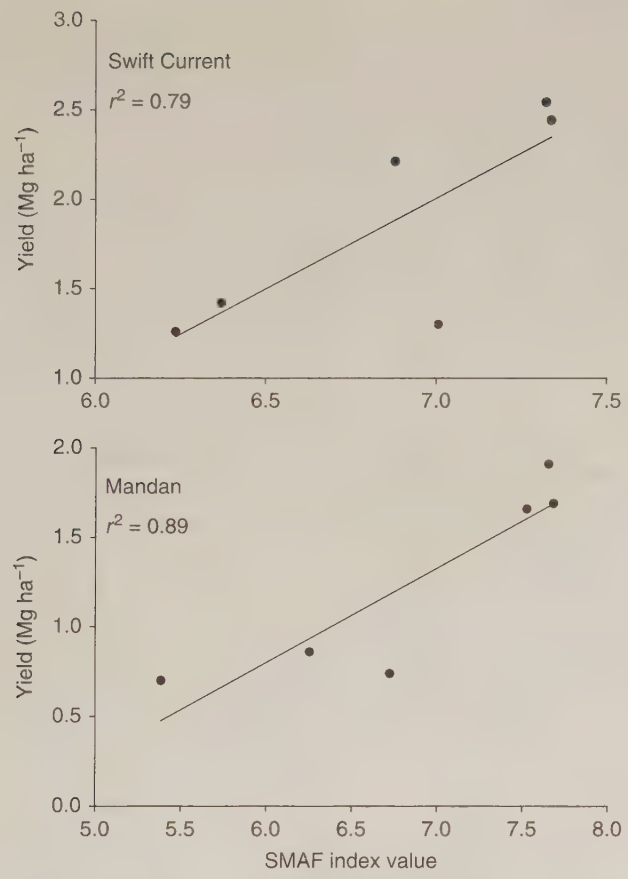

Figure 3. Correlation of soil management assessment framework (SMAF) index values and grain yield at two locations in the Great Plains. See Table 3 for correlation coefficients.

that improve soil quality resulting in improved crop yield over time.

There was a correlation between soil nitrate-N concentration at harvest and SMAF index values at all sites except Akron, Mandan, and Swift Current (Table 3). Soil nitrate-N concentration can serve as an indicator for an environmental goal since nitrate-N is readily leached below the root zone and potentially to the ground water. At Bushland, Fargo, Mead, and Sidney the correlation between nitrate-N concentration and SMAF index values was negative, while at Brookings the correlation was positive (Fig. 4). Soil nitrate-N concentrations at Brookings were low for a corn-based system, well below the threshold for environmental risk. At low soil nitrate-N concentrations, this property can serve as an indicator for an agronomic goal since N is the mineral nutrient most often limiting crop production in the Great Plains and as soil nitrate-N increases we would expect productivity to also increase.

At Fargo, Mandan, Mead, and Swift Current, there was a positive correlation between SMAF index values and organic C (Table 3 and Fig. 5). While soil organic C is a component of the SMAF index, the magnitude of the difference in index values between treatments at these sites is greater than the effect of one indicator in the index. The positive correlation is likely due to the effect soil organic C has on other indicators (e.g., aggregation and bulk density) in the index. Soil organic C can serve as an indicator for an agronomic goal due to its role in nutrient cycling, soil structure, and water infiltration and storage[15]. Soil organic C can also serve as an indicator for an environmental goal due to the soils role as a major pool in the global C cycle[19]. To serve as an assessment tool, values for the SMAF index should increase when soil organic C values increase for both the agronomic goal and the environmental goal.

There was a correlation between the SMAF and one or more indicators of soil function at all locations except Akron, suggesting that the framework has potential as a soil management assessment tool. Lack of a relationship between the SMAF and indicators of soil function at Akron is likely due to the relatively short time that the treatments at this location had been in place and the slow rates of change that occur at locations receiving low amounts of precipitation and having low production levels[3].

AEPAT index values

Food production function AEPAT values differed between the two treatments at Brookings (ALT treatment >CON treatment); varied from year-to-year at Bushland (2000 < 2001), Fargo (2000 > 2001 and 2002), and Swift Current (2000 > 2001), and exhibited a year-by-treatment interaction at Mandan (ALT treatment in 2000 > ALT treatment in 1999 and CON treatment in 1999 and 2000) and Mead (CON Treatment in 2001 and 2002 > CON treatment in 1999 and 2000 and ALT treatment in 1999–2002) (Table 4). As soil conditions required for crop production improve, food production function values increase. Year-to-year variability reflects the dynamic nature of soil pH and nitrate concentration. Use of a scoring function facilitates identification of times when soil property values cross a threshold value. At sites where treatment differences were observed, scored values for the ALT treatments were usually greater than those from the CON treatment, reflecting the improvement in soil conditions that has occurred when fallow is eliminated, crop rotation is used, and tillage is reduced. The lack of treatment differences at Mead is likely due to the use of similar tillage in both CON and ALT treatments at this site.

Nutrient cycling function AEPAT values differed between the two treatments (ALT treatment >CON treatment) at Brookings, Fargo, and Mandan; varied from year-to-year at Brookings (2001 > 1999, 2000 and 2002), Bushland (2000 > 2001), Fargo (2000 and 2001 > 2002), and Mead (1999 and 2000 > 2001 and 2002); and exhibited year-by-treatment interactions at Akron (ALT treatment in 1999 > ALT treatment in 2000 and CON treatment in 1999 and 2000) and Swift Current (ALT treatment in 2001 > CON treatment in 2001 and 2002) (Table 4). Increases in nutrient cycling function values result from efficient utilization of inorganic N by the crop (low post-harvest soil nitrate concentration) and improvement in soil organic C content (larger organic nutrient pool that can supply

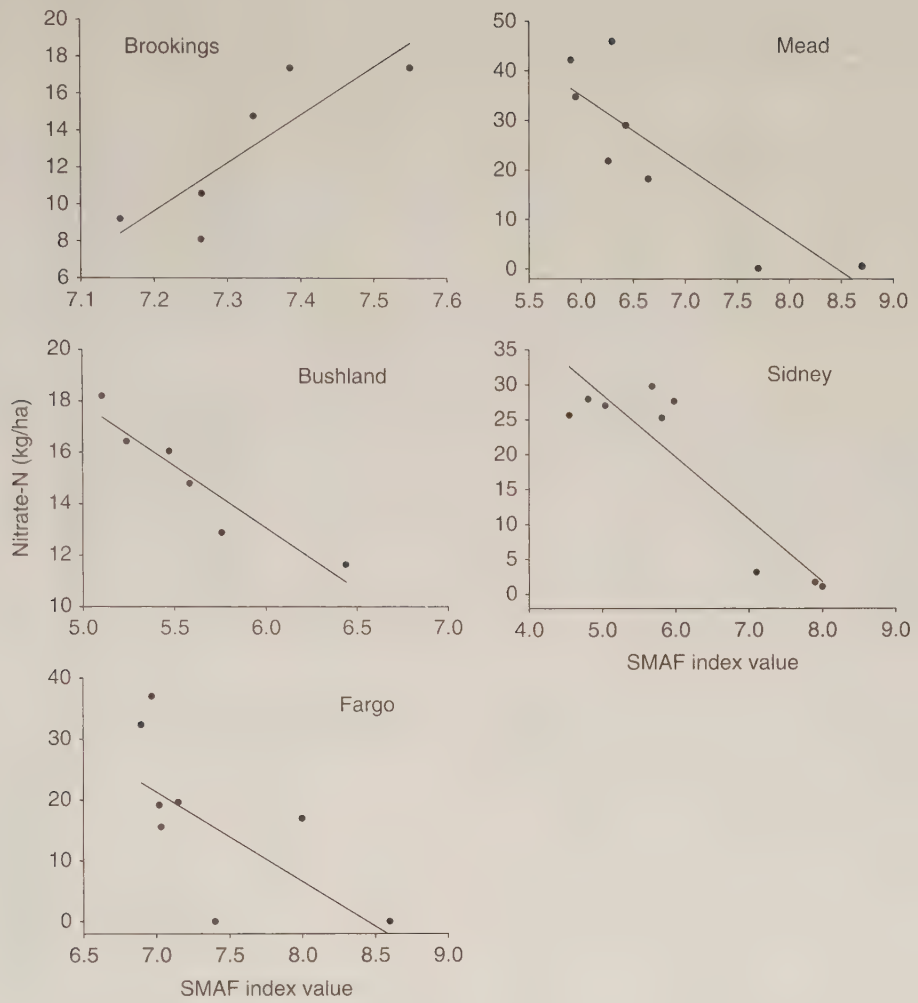

Figure 4. Correlation of soil management assessment framework (SMAF) index values and soil nitrate content at harvest for five sites in the Great Plains. See Table 3 for correlation coefficients.

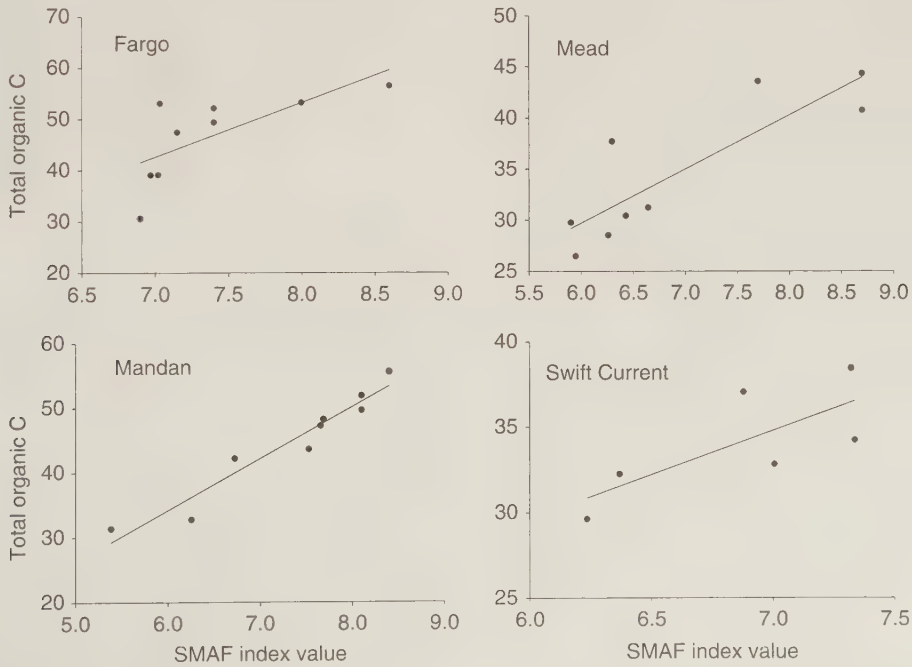

Figure 5. Correlation of soil management assessment framework (SMAF) index values and soil organic C content for four sites in the Great Plains. See Table 3 for correlation coefficients.

Table 4. *P*-values for main effects and interactions for food production and nutrient cycling functions and agro-ecosystem performance assessment tool (AEPAT) scores for eight sites in the Great Plains.

	Location							
Effect	**Akron**	**Brookings**	**Bushland**	**Fargo**	**Mandan**	**Mead**	**Sidney**	**Swift Current**
	P-value							
Food Production Function								
Treatment	0.69	< 0.01	0.42	0.12	< 0.01	< 0.01	0.11	0.21
Time	0.37	0.19	0.07	< 0.01	< 0.01	< 0.01	0.12	0.02
Tmt × time	0.24	0.55	0.53	0.14	< 0.01	0.02	0.48	0.71
Nutrient Cycling Function								
Treatment	0.14	< 0.01	0.24	0.01	0.07	0.22	0.38	< 0.01
Time	0.02	< 0.01	0.06	0.01	0.40	0.02	0.17	0.03
Tmt × time	0.07	0.44	0.13	0.11	0.70	0.15	0.35	< 0.01
AEPAT Score								
Treatment	0.72	< 0.01	0.79	0.72	0.03	0.12	0.22	0.30
Time	0.32	0.32	0.16	< 0.01	0.10	< 0.01	0.14	< 0.01
Tmt × time	0.21	0.26	0.85	0.06	0.21	0.01	0.42	0.27

Tmt, treatment.

nutrients to subsequent crops). Temporal variability reflects differences in crop utilization of inorganic N. Differences between treatments reflect the increase in soil organic C that occurs when the incidence of fallow is reduced and intensity of tillage is reduced and a reduction in the accumulation of soil nitrate that occurs with fallow. Lack of a treatment difference at Mead reflects the lack of fallow and similar tillage practices in both treatments. As reported by Varvel[20], soil C changes were similar in monoculture corn and the 4-year rotations at this site.

The food production and nutrient cycling function values were used to calculate AEPAT scores for each treatment and year. At Brookings and Mandan, AEPAT scores differed between the two treatments with the ALT treatment exhibiting higher scores than the CON treatment at both sites (Table 4, Fig. 6). Higher AEPAT scores in the ALT treatment reflect improved soil conditions that occurred when crop rotation was used at Brookings and the incidence of fallow and intensity of tillage was reduced at Mandan. The AEPAT scores varied from year-to-year at Mandan and Swift Current with higher scores in 2000 than in 1999 at both sites (Table 4, Fig. 7). The AEPAT scores exhibited a year-by-treatment interaction at Fargo and Mead (Table 4). At Fargo, AEPAT scores for the ALT treatment were greater than those for the CON treatment in 2000 and 2001, but were less in the ALT treatment than in the CON treatment in 2002 (Fig. 8). At Mead, AEPAT scores were similar across years in the ALT treatment and were less in 1999 and 2000 than in 2001 and 2002 in the CON treatment (Fig. 8). Many soil properties exhibit temporal variability, making dynamic assessments essential. The utility of the AEPAT is that soil values that may be difficult to interpret without extensive experience and knowledge are converted to easily interpreted scores for which greater is always better.

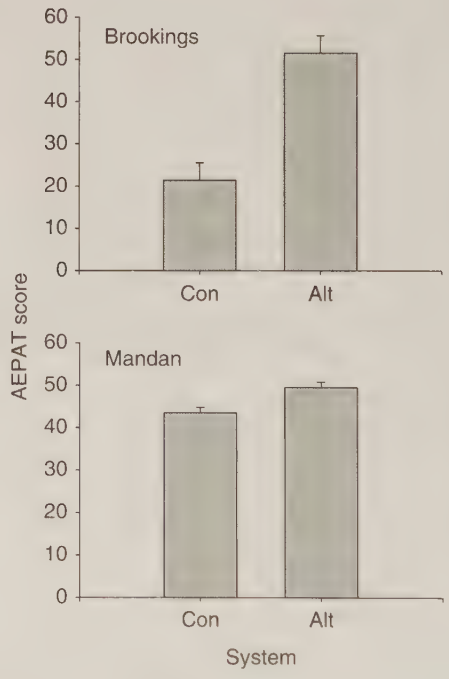

Figure 6. Agro-ecosystem performance assessment tool (AEPAT) scores as a function of management treatment for two locations in the Great Plains. Error bars represent 1 SEM.

Conclusions

The cropping system experiments used in this study have greatly improved soil and crop management by improving our understanding of how practices such as residue management, crop rotation, fertilization, and reduced incidence of fallow increase productivity and economic returns. These long-term research sites have been used for studies (economics and C sequestration), such as the one reported

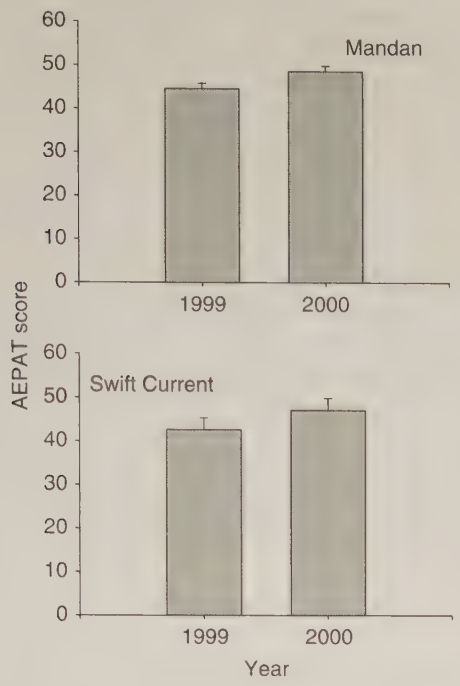

Figure 7. Agro-ecosystem performance assessment tool (AEPAT) scores as a function of year for two locations in the Great Plains. Error bars represent 1 SEM.

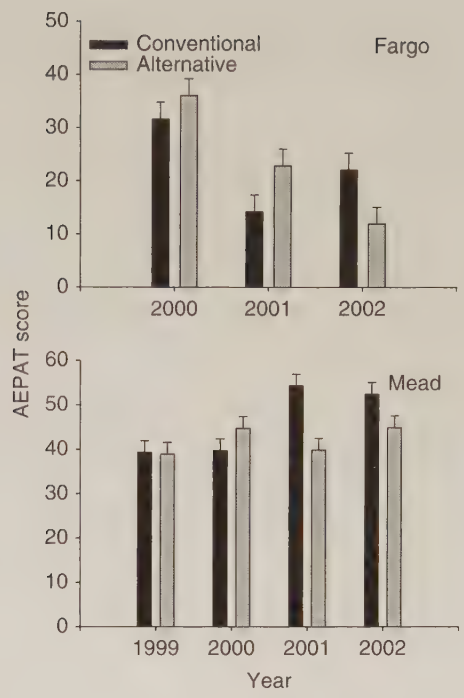

Figure 8. Agro-ecosystem performance assessment tool (AEPAT) scores as a function of management treatment and year for two locations in the Great Plains. Error bars represent 1 SEM.

here, that were not included in the original objectives[8]. These research sites, with their well-documented management, sampling, and analytical procedures, are a resource for local producers and a network for the study of regional (e.g., cropping systems), national (e.g., soil erosion), and global problems (e.g., greenhouse gas emissions). Methods for interpreting large data sets are needed. Statistical methods are useful for determining differences and trends in the data, but assessment tools that interpret how these differences and trends relate to essential system functions are needed to complement statistical approaches. Two assessment tools were implemented in this study.

Assessment tools

Both of the assessment tools used in this study are readily available but are also undergoing continuing development[12,14]. The SMAF is intended for use by land managers and their advisors for use in assessing ongoing management practices[12]. The scoring curves in SMAF require only indicator data along with crop and soils information. The crop and soils information is used by the program to adjust the scoring curves for the effect of inherent soil properties, climate, and crop response. Users of the SMAF do not need extensive knowledge of the relationship between soil indicators and management goals to utilize the framework. Scoring curves for 11 indicators are available in the current version of the SMAF and these scoring curves use indicator data for the 0–15 cm depth[12]. Therefore, the use of SMAF requires that samples are collected from the 0–15 cm depth and only the currently included indicators can be utilized.

The AEPAT is designed for agricultural researchers working with long-term agro-ecosystem experiments[14]. The AEPAT allows the user to select whatever indicators are thought to be important for evaluating a particular function. The user must also select the type of curve (e.g., sigmoid curve for pH) and threshold values (e.g., pH optimum of 6.5 for wheat and 6.3 for corn) for each indicator. The user also provides weights for indicators and functions to reflect their relative importance to the management goal. The input demands of AEPAT require that the user have a thorough understanding of how indicators relate to management goals. The AEPAT allows for more flexibility in terms of indicators (e.g., any indicator that affects the management goal and has a known relationship to that management goal) and sampling requirements (samples are not limited to the 0–15 cm depth increment).

Since the input requirements and intended uses of the SMAF and AEPAT are different, it is unrealistic to expect a high degree of correlation between the two indices, and inappropriate to make direct comparisons between them. However, since both programs are intended as tools for assessing the impact of management practices on essential agronomic and environmental functions, there should be a general agreement. The reason for using both assessment tools in this study relates to our third objective of assessing recently developed tools and methods.

Soil indicators

Pikul et al.[9] pointed out that spatial variation exhibited by point measurements of physical properties such as

infiltration are influenced by other measurements such as bulk density (compaction), making it difficult to detect existing treatment differences. Water-filled pore space was identified as a composite measure (calculated using bulk density, water content, and particle density) having utility for calculating probability functions that could be used to compare the likelihood of greenhouse gas emissions between treatments at a location. They also confirmed that aggregate stability was sensitive to management and that the erodible fraction had higher C concentrations resulting in preferential loss of organic matter when soil is lost via wind erosion.

Of the chemical soil properties measured, soil organic matter (SOM) and its component, particulate organic matter (POM), were sensitive to management, but this response was restricted to the 0–7.5 cm depth[10]. At several locations, SOM increased in the ALT treatment which included less fallow and lower tillage intensity. The more intensive cropping that results when the incidence of fallow is reduced increases biomass inputs to the system. Reduced tillage results in a less oxidative soil environment and maintains crop residues on the soil surface where they are less accessible to decomposers in the soil[21]. The identification of POM as a component of SOM that is sensitive to management in this study is significant since a new method for measuring POM was used[22]. This POM method does not require specialized equipment and is therefore easily implemented by users. This study also confirmed the utility of EC as an estimator of soil nitrate concentration in non-saline soils[23].

Liebig et al.[11] concluded that treatment effects on measured biological properties were concentrated in the 0–7.5 cm depth increment. Many of the trends in biological properties could be explained by knowledge of management impacts and weather conditions. There is a strong interaction between chemical and biological properties, and the fact that differences between treatments for both chemical and biological effects were most prevalent in the surface layer is not surprising. As discussed above, reducing tillage intensity affects the accessibility of crop residue to soil micro-organisms. Over the time there is an increase in SOM in the surface increment and this enriched layer supports higher microbial biomass and exhibits greater potentially mineralizable N. This study evaluated the usefulness of several emerging methods. Fatty acid methyl ester (FAME) profiles were useful for quantifying soil biomass and identifying differences in abundance of groups of organisms. Glomalin concentration was not as strongly related to aggregate stability in these semi-arid soils as in soils from more mesic areas[24]. Determination of FAME profiles and glomalin concentration both require specialized equipment and, while they are useful research tools, they probably will not gain acceptance as routine assessment tools. In contrast, the microwave irradiation method for determining microbial biomass[25] is a viable method that allows for the measurement of this biological soil property without the use of toxic chemicals.

Physical, chemical, and biological soil properties measured in this study and index values from the two assessment tools all exhibited temporal variation, which was likely related to weather and its interaction with sampling accuracy, previous crop in a rotation, and the dynamic nature of many of the properties measured. This study demonstrates that dynamic assessments are essential since temporal variation precludes recommending a single best sampling time. Dynamic assessments are especially useful in determining the direction of change. This study also demonstrated that sampling depth increments need to be selected with care. While changes in many chemical and biological soil properties were most apparent in the surface increment, other changes may be present in narrow increments within the profile (e.g., compaction layer due to wheel traffic or a tillage pan) and sampling in large increments may preclude detection of these important features.

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Energy use and efficiency in two Canadian organic and conventional crop production systems

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Abstract

A goal in sustainable agriculture is to use fossil fuel energy more efficiently in crop production. This 12-year study investigated effects of two crop rotations and two crop production systems (organic versus conventional management) on energy use, energy output and energy-use efficiency. The grain-based rotation included wheat (*Triticum aestivum* L.)–pea (*Pisum sativum* L.)–wheat–flax (*Linum usitatissimum* L.), while the integrated rotation included wheat–alfalfa (*Medicago sativa* L.)–alfalfa–flax. Energy use was 50% lower with organic than with conventional management, and approximately 40% lower with integrated than with the grain-based rotation. Energy use across all treatments averaged 3420 MJ ha^{-1} yr^{-1}. Energy output (grain and alfalfa herbage only) across treatments averaged 49,947 MJ ha^{-1} yr^{-1} and was affected independently by production system and crop rotation. Energy output in the integrated rotation was three times that of the grain-based rotation; however, this difference was largely due to differences in crop type (whole plant alfalfa compared with grain seed). Energy output was 30% lower with organic than with conventional management. Energy efficiency (output energy/input energy) averaged to 17.4 and was highest in the organic and integrated rotations. A significant rotation by production system interaction ($P < 0.05$) indicated that energy efficiency increases due to crop input reduction (i.e., shift from conventional to organic management) were greater in the integrated than in the grain-based rotation. Greater energy efficiency in the integrated rotation under organic management was attributed to the fact that the forage component was less sensitive to chemical input removal than grain crops.

Key words: crop rotation, organic, energy, legumes

Introduction

The energy efficiency of industrial agriculture has been questioned for decades[1]. The vast majority of energy used in crop production is in the form of fossil fuels[1]. Researchers have investigated more energy-efficient food-production systems, such as those that include legumes in rotation, and those that require less tillage[2]. More recently, researchers have become interested in exploring energy efficiency of organic farming systems. Organic systems were found to be more efficient than conventional systems for the production of milk in Germany[3] and cereal grain in northern US[4]. There is, however, a general lack of information on how organic management affects energy dynamics.

Three main components of an on-farm energy balance are energy use, energy output (energy stored in agricultural products) and energy-use efficiency. Energy consumption should account for all energy inputs, including energy to manufacture farm machinery, fertilizer, pesticides and energy embodied in liquid fuels and seed. A detailed accounting of energy used in all aspects of crop production in western Canada has recently been completed[5]. The second component of the energy balance is energy output. By all accounts, food energy output will need to increase in the future in order to satisfy a growing human population[6]. The final energy component of interest is energy-use efficiency. Given the limits to global energy supplies, it follows that using energy most efficiently in terms of food

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production is an important strategy. In the present study, energy-use efficiency is defined as the energy embodied in crop products per unit of crop input energy invested in the production system.

In many cropping systems, mineral fertilizers account for the largest proportion of the energy budget. Fertilizer accounted for approximately 70% of energy use in eastern Canadian corn production[7]. Almost 90% of commercial energy used to produce mineral fertilizer is for nitrogen (N) fertilizer[8]. Nitrogen fertilizer use has increased dramatically during the past 30 years. In 1982, N fertilizer accounted for 30% of energy use in North American cropping systems[9]. Globally, consumption of N fertilizer increased from 45 Tg in 1975 to almost 80 Tg in the mid-1990s[10]. The role of these N fertilizer increases in sustaining the growing human population is clear. For example, Smil[11] estimates that 40% of dietary protein is currently derived from the Haber–Bosch process. At the same time, overuse of N fertilizer in certain production regions of the world has not only wasted energy but also damaged the environment[2].

Growing legumes offers the opportunity to add N to the soil system biologically[12,13], which reduces fossil fuel costs associated with mineral fertilizer. Research in Manitoba showed that net soil N supply was increased by 148 kg N ha^{-1} when a 3-year alfalfa (*Medicago sativa*) crop was grown[14], while net soil N supply was only increased by approximately 20 kg N ha^{-1} when grain legumes such as pea (*Pisum sativum* L.) were grown[15]. Residual N benefits from perennial alfalfa were observed for 6 years; even up to 15 years after alfalfa termination[13]. Perennial legumes also help to suppress certain insect, disease and weed pests[13,16], reducing pesticide use.

The Glenlea long-term study was established in 1992 to determine the overall sustainability of organic compared with conventional crop production. Crop yield and soil nutrient results have been published elsewhere[17]. In this study, we measured energy use, energy output and energy-use efficiency in a grain-based and an integrated forage–grain rotation.

Materials and Methods

Glenlea long-term experiment

A crop-rotation experiment was established in 1992 at the University of Manitoba research station at Glenlea, Manitoba (49° 63′ N, 97° 13′ W), approximately 20 km south of Winnipeg. The soil type is a rego black chernozem with 9% sand, 26% silt and 66% clay (frigid Mollic Udifluvent). Two 4-year rotations from the study were examined: wheat–pea–wheat–flax (*Linum usitatissimum* L.) (designated the grain-based rotation) and wheat–alfalfa–alfalfa–flax (designated the integrated forage–grain rotation). Each rotation type was managed using either conventional management (pesticide and fertilizer applied according to standard recommendations) or organic management. No manure was applied to any of the organic plots. Treatments were arranged in a randomized complete block design in a factorial arrangement with only one rotation phase present in any given year. The experiment was replicated three times. Main plot size was 90 m × 60 m, with subplots measuring approximately 45 m × 30 m. Three 4-year rotation cycles were completed between 1992 and 2003.

Field operations

All crops were seeded in late April to late May using a disc drill seeder. Crops were seeded into a prepared seedbed, which had been cultivated within a few days of seeding. Alfalfa in the forage rotation was interseeded with wheat in the first year of the rotation, and was harvested in the second and third years of the rotation. Phosphorous fertilizer was applied to the conventional treatments as monoammonium phosphate with the seed, but broadcast on to established alfalfa. Ammonium nitrate fertilizer was applied at seeding and broadcast top-dressed at the 4-leaf stage. No animal manures were applied to the organic plots. Tillage involved 1 or 2 fall operations and at least one preseeding tillage operation in spring. The same number of tillage operations was used in the conventional and organic systems with one exception: after alfalfa termination, 2 or 3 more tillage operations were used in organic versus conventional systems. Tillage equipment included sweep cultivators and harrows; no inversion tillage was performed. Weeds were controlled in the conventional treatments with herbicides and tillage. Weeds were controlled in the organic system with occasional light harrowing once per year immediately prior to crop emergence. Alfalfa was terminated with herbicide (conventional treatments only), followed by tillage (forage was disked and cultivated). All field operations were performed with commercial farm equipment[17].

Grain yield of wheat, pea and flax was determined each year by harvesting an area within each plot using a small plot combine. In the first year of the study (1992), wheat was not harvested separately for individual experimental units and so no treatment effects were measured. Based on visual assessment, plot variation in wheat yield was minimal in 1992. The pea crop in 2001 died in mid-season due to excess water. Alfalfa dry matter production was determined each year by cutting three 1 m^2 samples from each plot, oven-drying (70°C) and weighing the samples. Details of field operations, soil nutrient status and crop yields over the 12-year study period (1992–2003) were presented elsewhere[17].

Energy budget

Twelve years of data (from 1992 to 2003) were used to construct the energy budget in this study. Data collected included crop input (seed, fertilizers, pesticides and fuel and machinery needed for all field operations) and crop yield for each treatment[17]. This information was then converted into energy values (MJ ha^{-1}) using energy

Table 1. Input energy coefficients for field operations carried out at the Glenlea long-term cropping systems study, 1992–2003 (Nagy, 1999).

Operation	Description	Tractor used	Total energy (MJ ha^{-1})
Pickup truck[1]	1/2 ton, gasoline	–	130.3
Fertilizer spreader[2]	14 m	85 HP	90.8
Water truck[2]	4 ton, gasoline, 7.2 km	–	8.7
Sprayer[2]	20 m	85 HP	41.9
Grain truck (seeding)[2]	4 ton, gasoline, 7.2 km	–	14.1
Disk drill[2]	20 m	165 HP	137.4
Cultivator w/harrows[2]	17 m	180 HP	124.2
Heavy duty cultivator[2]	11 m	180 HP	287.6
Tandem disk[2]	9 m	165 HP	317.1
Harrow packers[2]	25 m	165 HP	97.1
Swather[3]	6 m, single swath	85 HP (self-propelled)	161.7
Combine[3]	4.5 m	240 HP (self-propelled)	303.7
Grain truck (harvest)[3]	4 ton, gasoline, 7.2 km	–	113.9
Grain truck (market)[3]	4 ton, gasoline, 25 km	–	203.0
Mower/conditioner[2]	5 m	85 HP	182.9
Baler (round)[4]	454 kg bale	85 HP	465.3
Bale hauling[4]	10–14 bales, 3.2 km	100 HP	478.3

[1] Based on a 729 ha cultivated farm and 200 h of use per year.
[2] Energy coefficients are for 1 pass.
[3] Energy coefficients are based on a 2000 kg ha^{-1} harvest.
[4] Energy coefficients are based on a 9000 kg ha^{-1} harvest.

coefficients assigned for each crop input, field operation and crop harvested. Input energy coefficients for wheat, pea, flax and alfalfa seed used in the study were 7.2, 3.2, 14.0 and 6.9 MJ kg^{-1}, respectively[5]. Input energy coefficients were 67.03 MJ kg^{-1} of N for ammonia (34-0-0), 57.61 MJ kg^{-1} of N and 9.53 MJ kg^{-1} of P_2O_5 for monoammonium phosphate (12-51-0), and 1.12 MJ kg^{-1} of sulphur (S) for elemental S (0-0-0-95) fertilizers used in the study[5]. These energy values assumed only fertilizer production costs; fertilizer application energy costs were included in machinery and fuel use. Input energy coefficients for field operations carried out and pesticides used in the study are listed in Tables 1 and 2, respectively. Rotational energy use was calculated by adding the energy coefficients of all the field operations and crop inputs across all 12 years of the study. An average farm size of 729 ha (average farm size in Manitoba) was assumed for the energy budget, in order to establish a standard for equipment size[5].

Rotational energy output, also calculated across all 12 years of the study, was determined using energy output coefficients assigned to the different crops through laboratory bomb calorimeter tests. Coefficients were 18.71 MJ kg^{-1} for wheat, 18.64 MJ kg^{-1} for pea, 25.98 MJ kg^{-1} for flax and 17.77 MJ kg^{-1} for alfalfa[5]. The coefficients were based on grain weight for wheat, pea and flax, while the coefficient for alfalfa was based on dry matter weight[17]. Straw from seed crops was not included in the analysis; straw in Manitoba is typically left on fields and soil-incorporated. Energy efficiency was calculated for each treatment by dividing rotational energy output by rotational energy input on an annual basis. A second analysis for energy output and energy-use efficiency was conducted, where it was assumed that all alfalfa was fed to beef cattle for meat production and that the conversion factor from alfalfa hay into beef animal live weight gain was 9 : 1 (K. Ominski, personal communication, 14 April 2004)[18].

Statistical analysis

All analyses were conducted using Statistical Analysis System (SAS) version 8.2 for Windows (SAS Institute, Cary, NC). Factorial ANOVA tests were carried out on energy input and energy efficiency to detect rotation and system effects and interactions. The significance of F values was determined using $\alpha = 0.05$. It was not possible to complete the statistical analysis for energy input or C production, as there was no variation in input use between replicates.

Results and Discussion

Energy input

Total energy input for the 12-year study period is presented in Table 3. Average energy input for the conventional grain-based rotation (5708 MJ ha^{-1} yr^{-1}) was comparable to values in the Canadian literature[19].

Crop-rotation influence. The integrated grain–forage rotation used 27% less energy than the grain-based rotation in this study (Table 3). Less energy input in the integrated rotation was attributed mostly to less N fertilizer.

Table 2. Input energy coefficients for pesticides applied at the Glenlea long-term cropping systems study, 1992–2003 (Nagy, 1999).

Product	Common name	Total energy[1] (MJ ha^{-1})
Formulation: dispersible granules		
Achieve 40 DG	Tralkoxydim	62.0
Odyssey	Imazamox imazethapyr	8.9[2]
Formulation: dry flowable		
Refine Extra	Thiensulfuron + tribenuron	5.00
Formulation: solution		
Basagran	Bentazon	415.0
Horizon	Clodinafop-propargyl	20.2
MCPA A 500	MCPA amine	80.5
Roundup	Glyphosate	224.6
2,4-D amine	2,4-D	54.4
Formulation: granule		
Edge	Ethalfluralin	429.8
Formulation: emulsifiable concentrate		
Buctril M	Bromoxynil + MCPA E	187.6
Hoegrass II	Diclofop methyl + bromoxynil	449.0
Poast	Sethoxydim	62.9
Poast Flax Max	Sethoxydim + clopyralid + MCPA E	468.1

[1] Based on recommended application rates.
[2] Exact figure not available—calculated using average of group.

Table 3. Total rotational energy consumption at the Glenlea long-term cropping systems study, 1992–2003.

Rotation	Treatment	Seed energy	Fuel and lube energy	Machinery energy	Pesticide energy	Fertilizer energy	Total energy consumption
		MJ ha^{-1}					
WPWF[1,2]	Organic	7902	14,229	2102	0	0	24,233
WPWF	Conventional	7902	16,133	2367	7116	34,980	68,498
WAAF	Organic	3657	16,213	2311	0	0	22,181
WAAF	Conventional	3657	18,184	2515	3499	21,400	49,255

[1] W, wheat; P, pea; F, flax; A, alfalfa.
[2] WPWF, grain-based rotation; WAAF, integrated rotation.

For example, average annual energy input for N fertilizer in the grain rotation was 4362 MJ ha^{-1} for the first wheat crop, 290 MJ ha^{-1} for pea, 2546 MJ ha^{-1} for the second wheat crop and 3507 MJ ha^{-1} for the flax crop. In contrast, average annual energy input for N fertilizer in the integrated rotation was 3128 MJ ha^{-1} for wheat, 400 MJ ha^{-1} for each alfalfa crop and 2530 MJ ha^{-1} for flax. Therefore, average rotational energy input attributed to N fertilizer was 10,705 MJ ha^{-1} for the grain rotation and 6491 MJ ha^{-1} for the grain–forage rotation. Lower N fertilizer energy input in the integrated rotation was mostly due to less N fertilizer applied to alfalfa; however, residual alfalfa N also reduced N fertilizer requirements in flax and wheat crops. It should be noted that N fertilizer application to legume crops in the present study was the result of using ammonium phosphate as a P source. A number of previous studies have documented the important role that perennial legumes play in reducing N fertilizer requirement in crop production. In one study, alfalfa silage production used 37% less energy than corn (*Zea mays* L.) silage production[20]. In another study, a rotation of corn–corn–oat (*Avena sativa* L.)–alfalfa–alfalfa used 40% less energy than a 5-year continuous corn rotation[21]. In a third study, it was determined that alfalfa hay production used 30% less energy than barley (*Hordeum vulgare* L.) grain production. Again, this difference was due to decreased fertilizer requirements for alfalfa[22].

Less pesticide (301 MJ ha^{-1} yr^{-1}) and seed (354 MJ ha^{-1} yr^{-1}) use in the integrated compared with the grain-based rotation also contributed to lower energy input in the integrated rotation. Seed energy savings were due to less seed use during the perennial alfalfa phase and lower seeding rates in alfalfa compared with grain crops. While energy per kg of seed was similar for wheat and alfalfa, seeding rate for alfalfa in the second year of the rotation was much lower (10 kg ha^{-1}) than for the wheat crop (120 kg ha^{-1}). Less herbicide energy input in the integrated rotation was attributed to the absence of herbicide use

Table 4. Rotational energy output at the Glenlea long-term cropping systems study, 1992–2003.

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	Total	Amended total[1]
	(MJ ha^{-1})													
Rotation														
WPWF[2,3]	56,130	9179	51,993	36,861	42,431	35,560	24,153	25,771	26,591	0	25,284	24,995	358,948	358,948
WAAF	56,130	55,501	107,714	40,081	52,404	132,763	77,993	36,799	39,536	106,553	110,796	23,516	839,786	314,169
System														
Organic	56,130	33,929	80,932	30,321	31,319	77,149	37,614	25,780	16,955	45,807	51,943	9262	497,141	256,535
Conventional	56,130	30,751	78,775	46,622	63,516	91,174	64,531	36,790	49,172	60,746	84,137	39,249	701,593	413,523
Significance ($P>F$)														
Rotation (Rtn)	–	<0.0001	<0.0001	0.1948	0.0081	<0.0001	<0.0001	0.0652	0.0044	–	<0.0001	0.5860	<0.0001	0.1860
System (Sys)	–	0.2231	0.7058	<0.0001	<0.0001	0.1947	0.0043	0.0655	<0.0001	0.2384	0.0262	<0.0001	0.0012	0.0006
Rtn × Sys	–	0.9726	0.7099	0.0110	0.0884	0.9336	0.6143	0.1173	0.2127	–	0.3811	0.0154	0.8207	0.0798
SEM	–	1812	3898	1608	2014	7007	4827	3651	2337	16,583	8363	1843	29,736	20,392

[1] Assuming an alfalfa production : meat production conversion factor of 9 : 1.
[2] W, wheat; P, pea; F, flax; A, alfalfa.
[3] WPFW, grain-based rotation; WAAF, integrated rotation.

during the alfalfa phase, since alfalfa is competitive against weeds[23]. Herbicide use was similar in flax and wheat crops grown in the grain-based and integrated rotations.

Fuel and machinery energy inputs were 12 and 8% greater, respectively, for the integrated compared with the grain-based rotation. While the integrated grain–forage rotation required less fertilizer, herbicide and seeding energy, the cutting, baling and transporting of alfalfa hay used almost 50% more energy than the swathing, combining and truck transportation of harvested grain (Table 1). Energy input associated with alfalfa harvest would have been lower had the alfalfa been grazed instead of baled.

Organic versus conventional production. The difference in energy input between production systems (i.e., organic versus conventional) was greater than the difference between crop-rotation type (Table 3). When comparing the conventional and organic systems within rotations, the conventional system in the integrated rotation consumed 2.2 times the non-renewable energy as the organic system, while the conventional system in the grain-based rotation consumed 2.8 times the energy as the organic system. Fertilizer contributed most to the difference in energy input between conventional and organic systems, accounting for 51 and 43% of the total energy input of the conventional systems in the grain-based and integrated forage–grain rotations, respectively. Pimentel et al.[9] determined that fertilizer energy accounted for 30% of energy input in North American cropping systems in 1982, while Swanton et al.[7] found that up to 70% of energy in corn production was accounted for by mineral fertilizer use.

One criticism of organic farming is over-reliance on tillage for weed control, which increases the risk of soil erosion and increases machinery and fuel energy use. In the present study, tillage frequency averaged to 2.8 and 1.8 for the organic and conventional grain-based rotation, respectively, and 2.6 and 2.4 tillage operations yr^{-1} for the organic and conventional integrated rotation, respectively. These results indicate that tillage frequency was relatively low and that the difference in tillage frequency between organic and conventional systems was small. A North Dakota study found mean tillage events per year averaged 3.5 for conventional tillage farmers, 2.4 for organic farmers and 0.5 for no-till farmers[4].

Energy output

Few significant rotation × system interactions were observed for total rotational energy stored in agricultural products (i.e., energy output), indicating that crop rotation and crop production system affected energy output independently.

Rotation effects. Rotation effects for energy output were significant in more than half of the years. Greater energy output of alfalfa compared with grain crops (Table 4) was attributed to the fact that all above-ground alfalfa biomass was harvested in the integrated rotation,

Table 5. Rotational energy output and consumption, and energy efficiency at the Glenlea long-term cropping systems study, 1992–2003.

Rotation	Treatment	Energy output (EO)	Energy consumption (EC)	Energy efficiency	Amended energy efficiency[1]
		MJ ha^{-1}		(EO EC^{-1})	
WPWF[2,3]	Organic	252,054	24,233	10.4	10.4
WPWF	Conventional	465,841	68,498	6.8	6.8
WAAF	Organic	742,229	22,180	33.5	11.9
WAAF	Conventional	937,344	49,256	19.0	7.4
Significance ($P>F$)					
Rotation (Rtn)		< 0.0001	–	< 0.0001	0.2281 ns
System (Sys)		0.0012	–	0.0006	0.0018
Rtn × Sys		0.8207	–	0.0102	0.5657 ns
SEM		42,053	–	1.6	0.9

[1] Assuming an alfalfa production : meat production conversion factor of 9 : 1.
[2] W, wheat; P, pea; F, flax; A, alfalfa.
[3] WPWF, grain-based rotation; WAAF, integrated rotation.

whereas only the seed portion was harvested from corresponding pea and wheat crops in the grain-based rotation.

Rotation affected wheat and, to a lesser extent, flax seed yield. For example, a significant rotation difference for energy output was observed in years when wheat was the common crop in both rotations (1996 and 2000) (Table 4). Wheat grain yield was higher in the integrated compared with the grain-based rotation[17]. Flax was grown as the final crop in each 4-year rotation cycle (1995, 1999 and 2003). No significant ($P < 0.05$) difference in energy output was observed in any of the three flax years although, in 1999, flax energy output was higher in the integrated rotation at $P = 0.065$.

Organic versus conventional production. Averaged across the 12 years, energy output was approximately 40% higher in conventional than in organic systems (Table 4). Energy output was significantly higher under conventional versus organic management in the common wheat and flax crops in most of the years. Fewer energy output differences were observed among legume crops included in these rotations. For example, energy output of pea was never different in organic compared to conventional production (data not shown). Energy output was similar for organic and conventionally grown alfalfa crops except in 2002 when organically grown alfalfa stored less energy compared to conventionally grown alfalfa (data not shown). Entz et al.[17] speculated that lower alfalfa yield was due to low available soil P in the organic integrated rotation.

Converting forage energy into beef energy. Energy output values presented here assume equal energy availability of alfalfa and grain crops[5]. However, alfalfa biomass is typically fed to ruminant livestock, which are then consumed by humans, whereas grain crops can be directly consumed by humans. When the 9 : 1 ratio for energy conversion of forage to live animal gain (K. Ominski, personal communication, 14 April 2004)[18] was used (i.e., all other crop energy coefficients remained the same), no significant difference in energy output between rotations was observed (Table 4). However, an interaction ($P = 0.07$) between rotation type and production system indicated a difference in response of rotation to input management. For example, while energy output decreased with the shift from conventional to organic production in both rotations, the magnitude of the decline was less in the integrated rotation. Therefore, under low input management, an integrated rotation with additional N supplied via biological N fixation would be beneficial to production.

This analysis assumed that all grains were consumed directly by humans. However, peas and some wheat (weather-damaged crops) in Canada are typically fed to monogastric or ruminant livestock. The issue is clouded further when considering one-third of the grain produced in the world, and >80% of grain produced in the US, is fed to livestock, mostly cattle[24]. Therefore, when other end uses for grain crops are considered, energy output of grain-based cropping systems may, in fact, be much lower than those of integrated forage–grain systems.

Energy efficiency

Interaction between rotation and management system. There was a significant interaction between rotation and management system on energy efficiency (Table 5). The basis for this interaction was greater enhancement in energy efficiency moving from conventional to organic management in the integrated grain–forage system (175% increase) than in the grain-based rotation (152% increase). This differential response may have been related to the ability of alfalfa to supply N to the soil system[14] and to suppress weeds[23]. Due to these attributes, productivity under organic management in the integrated forage–grain system did not suffer as much as productivity of the grain-based system when subjected to organic management.

Rotation effects. Averaged across organic and conventional systems, the integrated forage–grain rotation had an

energy efficiency level that was three times higher than the grain-based rotation. Higher energy efficiency in the integrated compared with the grain-based rotation was attributed to both greater energy output and lower energy input in the integrated rotation. The higher energy output in the integrated rotation was largely due to alfalfa, but also from wheat crops in 1996 and 2000 (Table 4). When energy efficiency was calculated using a 9 : 1 ratio for alfalfa to live animal gain, no rotation effect for energy efficiency was observed (Table 5).

Organic versus conventional production. Averaged across rotations, energy efficiency was 40% higher for the organic compared with the conventional system. Higher energy efficiency for the organic system was primarily due to lower energy input (Table 3). While output energy was higher in the conventional system in both rotations, this increase was not sufficient to offset the higher amounts of input energy in conventional production. Cropping system was also significant for energy efficiency when the 9 : 1 conversion ratio was used for alfalfa (Table 5). Therefore, the organic system was still more energy efficient than the conventional system when all alfalfa harvested was 'fed' to beef cattle.

Comparison of energy efficiency between cropping systems must be done with care, as not all differences between systems may be accounted. In the present study, one factor that was not accounted was soil P. It is well known that organic systems, especially those containing hayed alfalfa, effectively extract P from soils, resulting in lower levels of inorganic soil P[25]. In the present study, soil inorganic P in the organically managed integrated system was lower at the end of 12 years than in the grain-based system (46, 33, 24 and 11 kg available P ha^{-1} for grain-based conventional and organic, and integrated conventional and organic systems, respectively[17]). In order to properly assess P deficits in organic systems, a full accounting of P in all soil fractions is required (focus of current work at Glenlea). Management options to overcome any P deficiencies in organic production include adding livestock manure or rock P; however, these practices were not included in the present study.

Summary and Conclusions

This study investigated energy inputs in two crop rotations under conventional and organic management. Energy input was affected more by management system than by crop rotation, although both were important. Energy input in the organic management system was approximately 50% lower than in the conventional management system. Energy input in the integrated forage–grain rotation was approximately 40% lower than in the grain-based rotation. Reduction in energy input was primarily due to reduction in N fertilizer use.

Crop rotation and management system affected energy output independently. The integrated forage–grain rotation produced almost three times the energy as the grain-based rotation. However, when alfalfa hay energy was converted into animal live weight gain energy, no difference in energy output between crop rotations was observed. Energy output was 30% lower with the organic system than the conventional system. Lower energy output for the organic system was attributed mainly to lower flax and wheat yields, although low organic alfalfa yield also contributed.

Energy efficiency (energy output/energy input) of all systems averaged to 17.4. Energy efficiency increased as energy inputs were reduced (i.e., the change from conventional to organic production); this increase was greatest for the integrated rotation.

Of the three energy parameters tested, the organic system outperformed the conventional system on the basis of lower energy input and higher energy efficiency. Similar observations have been reported by others[3,4]. Organic systems were not able to match the energy output of conventional systems. Therefore, one important conclusion from this study is that organic systems were less productive, energetically, than conventionally managed cropping systems, raising questions about long-term caloric production of organic agriculture. This conclusion distracts from the environmental benefits of organic crop production. It should be noted, however, that analysis in this study assumed that all grain crops would be used for human consumption. In many industrialized countries, a high proportion of grains are fed to ruminant and monogastric livestock. Therefore, future research should focus on energy production of integrated versus grain-based rotations where different proportions of the grain crops are used for livestock feed.

The present study pointed to the critical role of legumes, especially perennial alfalfa, for increasing the energy efficiency of a cropping system. For example, energy output in the lowest ranking system (i.e., the organic system) was increased dramatically when the rotation was changed from a grain-based rotation to an integrated forage–grain rotation. In fact, in the integrated rotation, the organic system showed a slightly higher energy output level than the conventional system. This observation suggests that organic systems can be designed to store energy at levels similar to, or even higher than, conventional systems.

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An economic comparison of alternative and traditional cropping systems in the northern Great Plains, USA

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Abstract

Current production practices in the Red River Valley of North Dakota and Minnesota involve use of extensive tillage and/or herbicides to control weeds. Given the erosion potential, environmental concerns associated with herbicides, and herbicide-resistant weeds, alternative cropping systems that mitigate these problems need to be assessed economically. Furthermore, the role that government commodity programs play in the adoption of more ecologically friendly cropping systems needs to be determined. We evaluated 8 years of yield data (1994–2001) from field plots near Fargo, North Dakota, to compare the economics of two alternative cropping systems, reduced-input (RI) and no-till (NT), to a conventional tillage (CT) cropping system. The RI system relies on a more diverse rotation of soybean (SB), spring wheat (SW), sweet clover (SC) and rye, and uses fewer herbicide and fertilizer inputs than CT or NT. Both NT and CT systems rotate SB and SW. We found that CT returns averaged over \$47 ha^{-1} more than NT during the study period. Because SC yield data were not available, the economic competitiveness of RI was calculated using break-even yields and returns for SC. Historical SC yields in Cass County, North Dakota were not statistically different from the break-even yields. However, when government program payments were considered, break-even returns for SC increased by about \$15 and \$18 ha^{-1} and break-even yields by 0.44 and 0.52 MT ha^{-1} for RI to compare with NT and CT, respectively. These results indicate that CT management offers greater economic return than either RI or NT and that government program payments impede adoption of more environmentally friendly cropping systems in the northern Great Plains.

Key words: reduced-input, cropping systems, sustainability, soybean, spring wheat, sweet clover, rye

Introduction

Cropping practices in the Red River Valley of North Dakota and Minnesota typically rely heavily on tillage and/or herbicides to control weeds. Rotations may include just two or three crops, e.g., soybean (SB)–wheat, require heavy fertilization, may be prone to disease problems and create the potential for herbicide-resistant weeds. Given potential erosion problems, environmental concerns regarding pesticides, herbicide-resistant weeds and high fertilizer prices (due to high energy prices), alternative cropping systems that can reduce reliance on tillage, herbicides and fertilizers are of interest to researchers and producers. Here, we compare the economic advantages/disadvantages of two alternative cropping systems, reduced-input (RI) and no-till (NT), to a conventional tillage (CT) system.

The CT system rotated SB and spring wheat (SW), employed fall tillage (disk harrow and field cultivator), spring tillage (field cultivator), fertilization at recommended rates and extensive herbicide treatments for weed control. The RI system rotated four crops, SB–SW–sweet clover (SC)–rye, employed mulch tillage (30% or greater residue), applied less than one-half of the fertilization of CT, and used only non-residual herbicides (post-emergence when necessary). The NT system was identical to CT except for the absence of tillage.

The purported advantages of RI include reduced weed pressures, reduced disease damage, increased nitrogen fixation and increased yields. Weed control represents 20–30% of input costs, and herbicides represent 85% of the pesticides applied to North Dakota fields annually[1]. Kegode et al.[2] reported that when crop diversity within a rotation

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was increased and tillage reduced, weed seed production over a five-year period was significantly reduced. When fewer seeds are added to the weed seed bank, weed densities in subsequent cropping seasons are potentially lower and herbicide costs are reduced.

RI rotations and crop diversification can break disease and weed cycles[3]. Moreover, longer crop rotations improve soil structure, and increase organic matter and water percolation. Furthermore, legumes help fix nitrogen after harvest[4]. Studies in Saskatchewan indicate that weed seedling and seed bank densities are similar or lower in RI rotations compared with high-input rotations[1]. Comparing the same CT, NT and RI systems analyzed in this study, Ramsdale et al.[5] reported that total weed density in wheat and SBs was generally highest in the early years following conversion from CT to RI. However, weed density was lowest in the RI system in later years. Winter wheat residues reduce weed seedling emergence by 45% and weed biomass by 60% on SB[1]. Introducing forage crops in a rotation has been shown to significantly improve yield[6]. Hoyt[7] reported that wheat following up to 8 years of alfalfa yields 66–114% more than wheat grown in a wheat–fallow rotation.

Adopting reduced tillage or RI rotations in the northern Great Plains may improve the economics of farming systems. Studies indicate that production costs are higher as the system becomes more intensive[8]. However, in RI systems farmers often reduce machine-related operating costs (fuel, oil and repairs) by decreasing the number of field operations, combining two or more operations (e.g., seeding and fertilizing) and using large capacity sprayers instead of tillage machinery, thereby lowering fuel, labor and repair expenses[9].

Crop diversification is an efficient means to reduce operating costs[10]. Zentner et al.[10] reported that costs of production for the rotations that include forages are lower than those for continuous grain production but higher than those for wheat–fallow systems. In addition, the stability of net returns across years is greater for rotations that include forages, which may reduce income variability and business risk[11]. However, NT, mulch tillage and crop diversification may require more time to manage pest problems, fertilization and marketing. In addition, adopting a new cropping system may increase business risk and require adjustment costs for the purchase of new equipment and for learning the use of new technologies[11]. Zentner et al.[12] reported that conservation tillage, e.g., mulch tillage and NT, may increase expenditures for herbicides by $\$11\,ha^{-1}$ with mulch tillage and $\$31\,ha^{-1}$ with NT fallow–wheat.

Switching from high-input CT to NT or RI cropping systems has both agronomic and economic impacts[13]. Farmer adoption of alternative systems, including RI and NT, depends on the relative economic returns of competing systems. The purpose of this study was to compare the economic return of NT and RI systems to a conventional SB–SW rotation under CT. We test the hypothesis that alternative cropping systems in the northern Great Plains can be economically competitive with conventional cropping systems.

Materials and Methods

Data were collected from experimental plots established in the fall of 1993 in Cass County, near Fargo, North Dakota. Data collection continued through 2001. The initial goal of the experiment was to evaluate weed density and diversity under three cropping systems, CT, NT and RI. However, the data collected are also useful for comparing the economic returns of these competing systems. The CT and NT systems rotated SB and SW, while the RI cropping system rotated SB, SW, SC and rye under mulch tillage. Unfortunately, SC yields were not collected during the trial, so in the economic analysis presented here we compute the break-even returns and yields necessary for the RI system to compete with NT and CT.

The field study was established on a Fargo silty clay soil (fine, smectitic and frigid-type nitraquerts) with a pH of 7.5 and 5.5% organic matter[5]. Fargo receives an average precipitation of $540\,mm\,yr^{-1}$ with an average growing season of 133 days from May 14 until September 24. During the experimental period, growing season temperatures were close to the 30-year average every year (1994–2001). The experimental site was managed using CT prior to the experiment and fallowed the year before beginning the experiment. The experiment was a randomized complete block design with three replicates. Plots were $14\,m \times 30.5\,m$ and separated by 2 m alleys within each replicate. On the outside, a 9 m wide border surrounded the experiment and the same distance separated the replicates.

In order to grow each crop every year in each rotation, eight plots were used in the rotation study, four for the RI system and two for the other two systems. Two sequences of the RI system and four sequences of the NT and CT systems were completed during the 8 years of data collection and analysis.

In all rotations, SW was seeded in late April or May, depending on weather, with a Haybuster NT drill at an 18-cm row spacing and a density of $112\,kg\,ha^{-1}$. Cultivars were 'Grandin' SW in 1994, NDSU '2371' SW in 1995, Pioneer '2375' SW in 1996 and 1997, 'Oxen' SW in 1998–2000 and 'Alsen' SW in 2001. CT and NT SB were seeded with a Haybuster NT drill in 18-cm rows. In the RI system, SB was seeded with a Hiniker NT planter at 76-cm row spacing in order to allow inter-row cultivation. Two different varieties, 'Ozzie' SB (1994–1997) and 'Trail' SB (1998–2001) were seeded in late May at $67\,kg\,ha^{-1}$ for all systems. The SC was seeded every year with Melroe Kirchman small-grain drill (15-cm row spacing) at $11\,kg\,ha^{-1}$. During the first two years of the study (1993 and 1994), SC did not survive the winter. Therefore, beginning in 1995, planting was done in the spring. The SC was harvested two to three times a year depending on the weather. Winter annual rye was seeded in September at a rate of $84\,kg\,ha^{-1}$ each year following SC. Rye was seeded

with a Melroe Kirschman small-grain drill from 1994 to 1998 and a Haybuster NT drill from 1999 to 2001. Two varieties were planted, 'Dacold' in 1994 and 1995 and 'Musketeer' in 1996–2001.

Fertilizers were applied based on soil sample analyses and the yield goals for each crop. Samples were taken at a 15-cm depth in the fall of each year to determine N, K, P, soil organic matter and soil pH. Granular fertilizer was applied in the spring before seeding SC, SW, SB and rye[5].

Weed management varied between systems. In CT, pre- and post-emergence herbicides and pre-plant and post-harvest tillage were employed. In NT, weed management included only foliar herbicides applied post-emergence or post-harvest. As RI was more diversified, so were the methods to control weeds. Management included pre-plant and post-harvest tillage, inter-row cultivation in SB, mowing in SC and minimal use of non-residual herbicides as weed management options for SW. No weed control was used in rye. Rye was mowed prior to reaching maturity. These weed control strategies were followed as much as possible, although adjustments had to be made each year according to weed pressures and weather conditions.

When used, RI tillage consisted of a tandem disk, field cultivator with harrow, chisel plow, V-blade sweep (76 cm) under cutter and an inter-row cultivator with a 60-cm V-blade sweep. The depth of cultivation with either the tandem disk and field cultivator was generally between 5 and 10 cm. The depth of cultivation when using an inter-row cultivator and V-blade sweep under cutter tillage was around 2.5–5 cm deep. Chisel plow treatments were 15–20 cm deep.

Prices and costs

Yields of every crop, except SC, were reported annually. Prices were obtained from the US Department of Agriculture (USDA) North Dakota Agricultural Statistics Service[14]. For SC prices, the 'Hay All, Baled' category was used. Fertilizer prices were taken from the North Dakota projected crop budgets for 2004[15]. All costs and prices in this study were deflated to 2001 dollars using a Producer Price Index[16]. Prices for N, P and K were \$0.39, \$0.44 and \$0.27 kg^{-1}, respectively. Herbicide prices were obtained from Zollinger[17]. Seeding, harvest, pesticide application costs and tillage operations were recorded annually. Tillage costs were taken from Lazarus and Selley[18].

Government program payments

During the study period, US farm programs offered subsidies to producers when prices of covered commodities fell below target levels or the loan rate. These subsidies, called loan deficiency payments, are calculated as the difference between the local prices and the loan rate. They are paid based on the production level or on a per bushel basis for SB and SW. Cropping systems with lower yielding program commodities, e.g., SB and SW, or with fewer hectares planted to program commodities, will receive lower subsidies. Loan rate data for Cass County, North Dakota were taken from information published by the USDA Economic Research Service[19].

Economic analysis

Revenues were computed on a per hectare basis by multiplying each crop yield by its corresponding price. Returns were computed for each year and crop by subtracting per hectare costs from revenues. To calculate and compare annualized returns for the different systems, each year's per hectare returns were weighted by the inverse of rotation length (two for NT and CT and four for RI) and summed. Average annual return by system was reported with and without loan deficiency payments. Comparisons between CT and NT average annual returns were made using *t*-tests (90% confidence).

Break-even yields for SC in the RI system were computed as the difference between the average return for CT or NT treatments and the RI treatment (without a return for SC). Break-even returns to SC and break-even yields were computed with and without loan deficiency payments. Break-even SC yield was obtained by dividing the break-even return by annual (1994–2001) average price of 'Hay All'. Finally, break-even SC yield was compared to published county yields for Cass County, North Dakota between 1995 and 2002[20]. A *t*-test, at 95% confidence, was used to compare the means of the historical Cass County, North Dakota, SC yields and break-even yield.

Results

Return by crop

Average annualized yields and summary statistics are reported in Table 1. Average annualized returns by crop are given in Table 2. Ignoring government program payments, SB had the highest average return within RI (\$137.89 ha^{-1})

Table 1. Annualized average yields by crop and system.

	Yield		
System	**SB**	**SW**	**Rye**
	----------MT ha^{-1}----------		
RI			
Average	1.47	1.87	3.11
Range	0.66–1.99	0.25–3.17	1.76–4.51
Standard deviation	0.48	0.93	0.95
CT			
Average	1.64	2.53	
Range	1.17–2.38	1.48–3.47	
Standard deviation	0.41	0.73	
NT			
Average	1.43	2.47	
Range	0.66–2.25	1.36–3.32	
Standard deviation	0.50	0.71	

Table 2. Average annualized return by crop and system.

System	Returns SB	SW	Rye
	----------$ ha [1]----------		
RI			
Average	137.89	88.15	87.11
Minimum	−90.60	−69.41	−132.4
Maximum	423.74	281.19	270.12
Standard deviation	146.73	120.95	120.28
Average with government program[1]	150.96		
NT			
Average	89.51	96.32	
Minimum	−117.09	−97.32	
Maximum	294.67	217.16	
Standard deviation	140.85	113.6	
Average with government program	103.70		
CT			
Average	124.14	156.89	
Minimum	−101.79	−80.93	
Maximum	335.35	282.61	
Standard deviation	131.78	105.07	
Average with government program	139.90		

[1] Loan deficiency payments occurred in 1998, 1999 and 2001 for SB.

Table 3. Average annualized return by system.

	Returns CT	NT	RI[1]
	----------$ ha^{-1}----------		
Average	140.52	92.92	85.15
Minimum	−91.26	−106.49	−73.10
Maximum	261.57	193.14	177.90
Standard deviation	100.45	89.10	73.99
Average with government program	147.52	99.23	88.05

[1] Excluding SC.

Table 4. Break-even results for SC.

	RI system compared to	Government programs Without	With
Breakeven return ($ ha^{-1})	CT	249.18	267.63
	NT	34.94	50.25
Breakeven yield (MT ha^{-1})	CT	7.18	7.70
	NT	1.01	1.45

followed by CT ($124.14 ha^{-1}). This was due to a combination of higher yields and lower production costs. Unlike SB, SW was more profitable under CT with an average return of $156.89 ha^{-1}, followed by NT ($96.32 ha^{-1}) and RI ($88.15 ha^{-1}), due primarily to higher yields under CT and NT. In addition, the highest maximum SW returns were found in RI and CT, $281.19 and $282.61 ha^{-1}, versus $217.16 ha^{-1} for NT. In RI, rye average returns were similar to SW ($87.11 ha^{-1}). The SC returns were not reported in this table as yield was not recorded.

Loan deficiency payments were available in 1998, 1999 and 2001 for SB. Consequently, average SB returns increased by $15.76, $14.19 and $13.07 ha^{-1} for CT, NT and RI, respectively, when these payments were considered. With these payments, average SB returns were highest in RI and lowest in CT, the same ranking as without program payment.

Return per system

Average annualized return by rotation is reported in Table 3. The CT system had an average return of $140.52 ha^{-1}, followed by NT ($92.92 ha^{-1}) and RI ($85.15 ha^{-1} without SC). Average return by system increased with government loan deficiency payments by $7.00, $6.31 and $2.90 ha^{-1} for CT, NT and RI, respectively. Note that comparisons between RI and the other two systems were not possible without SC yields. However, CT and NT can be compared. The CT system averaged $47.61 ha^{-1} more than the NT system, due to higher yields. Loan deficiency payments increase the economic advantage of CT over NT to $48.30 ha^{-1}. Using *t*-tests, the difference in return between CT and NT, with and without loan deficiency payments, was insignificant ($P \leq 0.10$). However, given the low number of observations (nine), the test lacks discriminatory power.

Break-even yields and returns

Break-even yields and returns are provided in Table 4. Without loan deficiency payments, SC had to generate an average return of $249.18 ha^{-1} annually for RI to be as profitable as CT, and $34.94 ha^{-1} for RI to be as profitable as NT. The SC had to yield 7.18 MT ha^{-1} for RI to be as profitable as CT and 1.01 MT ha^{-1} for RI to compete with NT. When compared with historic yields in Cass County, North Dakota, during the same period, the break-even yield of 7.18 MT ha^{-1} was realized 3 out of the 8 years of the experiment[20], indicating a 37.5% likelihood of achieving the SC break-even yield. Similarly, the break-even yield of 1.01 MT ha^{-1} was reached every year, indicating that RI was as profitable as NT. Under loan deficiency payments, the RI SC break-even yield increased to 7.7 MT ha^{-1} in order for RI to match CT return and 1.45 MT ha^{-1} for RI to match NT return. Thus, RI SC break-even yields were reached 100% of the time when

compared to NT but only 25% of the time (2 of 8 years) when compared to CT.

Statistical comparisons using *t*-tests were conducted to compare the means of historical Cass County, North Dakota, SC yields and break-even yields. Although, given the low number of observations (eight), the statistical test lacks discriminatory power, break-even and historical yields were not statistically different.

Conclusions and Implications for Producers

Alternative cropping systems, including RI and NT, are touted as having ecological benefits including reduced soil erosion, weed pressure, herbicide resistance, herbicide requirements and disease pressure, and improved water quality. However, agronomics and economics are driving factors in cropping system decisions.

Switching from CT to RI has the following agronomic and economic impacts for producers. First, SW and SB yields decline, mostly due to the proliferation of weeds from reduced herbicide inputs and reduced fertilizer rates. Even though yield differences were not large for SB (loss of $0.17\,MT\,ha^{-1}$), SW yield reduction was significant (around $0.7\,MT\,ha^{-1}$) over the time period of the experiment (1994–2001). Lower yields partially explain the lower revenues of RI. However, a concomitant reduction in operating costs is realized under the RI system, averaging $\$39\,ha^{-1}$. This difference can be explained by fewer trips across fields and reduced inputs, including herbicides, fuel and fertilizer. Although not investigated in this study, there may be additional potential for savings under the RI system due to economies of scale. As fewer trips on the field are required, larger acreage can be covered with the same machinery. Consequently, producers may be able to produce at lower costs by spreading fixed costs over greater acreage.

Switching from CT to NT has the following agronomic and economic impacts for producers. Average SB yield declines by $0.21\,MT\,ha^{-1}$. Yield variability increases, with both lower minimum and lower maximum yields. Similarly, SW average yield declines slightly by $0.06\,MT\,ha^{-1}$ and the minimum and maximum SW yields decline. While tillage costs also decline under NT, these are more than offset by the revenue losses associated with lower yields. According to the Conservation Technology Information Center[21], only 4.7% of North Dakota's cropland was planted using NT in 1995. While the use of herbicide-tolerant SB varieties has increased the use of NT and other reduced-tillage systems, the results reported here provide economic justification for the low percentage of NT. As with the RT system, fewer field operations associated with NT may result in economies scale.

We found that government programs create disincentives for farmers to switch from CT to RI or NT. Since the probability of reaching SC break-even yield was reduced from 37.5 to 25% with the inclusion of federal loan deficiency payments, it is not surprising that producers choose traditional cropping systems and tillage over the alternative RI system. Loan deficiency payments also increased the economic advantage of CT over NT, as SB and SW yields are higher under CT. While some government officials speak of a commitment to improved environmental quality, congressionally mandated commodity programs, such as loan deficiency payments, may encourage the perpetuation of less environmentally friendly cropping systems in the northern Great Plains by increasing their economic advantage.

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Book Review

Managing Soil Quality: Challenges in Modern Agriculture. Edited by P. Schjønning, S. Elmholt and B.T. Christensen. 2003. CABI Publishing, Wallingford, UK. 368 p. £75.00/US$140.00, HB 085199671X.

This volume includes a collection of chapters solicited from researchers working in Europe and North America. The work was supported by the Danish Ministry of Food, Agriculture and Fisheries to provide an overview of the influence of modern agriculture on soil quality. Through this publication the editors P. Schjønning, S. Elmholt and B.T. Christensen hope to revitalize the discussion of soil quality. To do so, they propose a framework for consideration that focuses on soil management with an emphasis on management-based thresholds as a means to implement the soil quality concept. This book will be of most interest to individuals in the scientific community who have contributed to this area or to advisors or practitioners following the discussion of whether or how the concept might help us manage the soil resource better.

In the preface, soil quality is defined as how well soil does what we want it to do. Chapter 1 addresses concepts and terms where the soil quality concept is presented as a human construct engineered with specific purposes. Chapter 2 also defines concepts and reviews the history of soil quality with an emphasis on the North American experience. Rather than focus on indicators, the editorial team asked contributors to identify management thresholds and research needs associated with: problems in modern agriculture (Chapters 3–6), maintenance of soil biology and biotic function (Chapters 7–9), protection of physical form (Chapters 10–12), avoidance of contamination (Chapters 13 and 14) and management of soil quality (Chapters 2 and 15–18).

The discussion in Chapter 1 will be of greatest interest to researchers who have been engaged in the discussion or development of the soil quality concept. In this chapter, Schjønning et al. acknowledge that some of the challenges the soil quality concept or its implementation have encountered stem from differences in opinion about the role science should play in society. They note that because agricultural sciences play a proactive role in the environment they study, these sciences cannot meet the scientific ideal of objectivity. The authors advocate that value-laden aspects of science be acknowledged while taking an objective stance with regard to the impacts prescriptions might have on other aspects of the system being studied. They note that applied scientists employ reflective objectivity within cognitive contexts; these contexts include societal and intentional dimensions that influence the experimental methods, relevance and objectives of their work. In this chapter, the editors present the themes of sustainability, resistance and resilience as central to soil quality. Unfortunately, ideas associated with these terms were not developed well enough or used consistently enough within the subsequent chapters to make them immediately useful to practitioners. Those interested in managing soil quality will find the discussion of challenges associated with the use of indicators and thresholds of greater practical value. They advocate the use of thresholds rather than benchmarks, baselines or reference states where thresholds are defined as points beyond which additional stimuli provoke negative, often rapidly occurring, accelerating, or relatively dramatic, consequences. Moreover, they note, when context and application are defined, characteristic properties or indicators can be used; however, when decisions about management are to be taken, then management-based thresholds should be used.

The series of chapters on problems in modern agriculture emphasize management and treat themes in an agronomic manner. Chapter 3 addresses soil acidity and management of pH; well-established amendment strategies are presented in terms of management thresholds. Chapter 4 provides a general synopsis of the nitrogen (N) cycle and an overview of strategies and management principles that might be relied on to tighten the N cycle. The author makes the important point that we must consider the dynamics of N in soil as well as that applied to increase the N use efficiency of farming systems. The chapter relies heavily on studies using isotopically labeled N sources and seems to equate fertilizer recovery with N use efficiency. Hopefully, the discussion of N dynamics occurring within different types of management systems and of the importance of synchrony between crop uptake and soil N supply will prevent readers from wrongly concluding that climate and amendment type are the major factors influencing the N use efficiency of production systems or that the root cause of N leaching is organic matter mineralization and due to the characteristics of the farming systems imposed on soils. Chapter 5 includes a well-researched summary of phosphorus (P) management strategies employed within different soils and agricultural systems. Appropriate use of both indicator- and management-based thresholds is discussed as are budgeting and spatially based assessment strategies. Chapter 6 reviews unique issues associated with potassium (K) management; emphasis is placed on efficient use rather than on environmental risk. The authors propose that a budgeting approach be used to manage low-K input systems where, despite known limitations, soil- and plant-based tissue testing strategies are used to ensure soils supply critical levels of K appropriate to the crops grown.

The group of chapters covering organic matter and biotic diversity is variable in nature. Chapter 7 reviews factors influencing soil organic matter levels and provides a basic coverage of this theme that is consistent with other recent publications. Management practices are classified

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according to whether their use will increase or decrease organic matter levels. The inclusion of management thresholds would have strengthened this chapter. Chapter 8, which discusses microbial diversity in relation to crop health, focuses on microbial contributions to disease suppression. This chapter is one of the most original chapters in the book and includes a review of potential indicators and management of soil function. The discussion of thresholds has freshness missing in some other sections. Chapter 9 discusses the contributions of the microbial biomass to stability and resilience of soil quality. The discussion of biotic function and indicators is well done but the authors draw primarily from references explicitly associated with soil quality. Inclusion of more basic literature that reflects recent advances in both the methods and their interpretation may have strengthened the chapter. The critique of indicators included in this chapter is intriguing; I only wish the basis for their conclusions was discussed in more detail. Even though they note the importance of soil biodiversity, they ask whether biological soil quality indicators are necessary at all. This and other questions raised will need to be answered before biotic indicators or thresholds are implemented.

Chapters focusing on soil degradation return to a somewhat traditional approach by relating soil quality to soil management. This appropriately reflects the fact that the soil quality concept must be related explicitly to practices or cropping strategies in order to be made useful. Chapter 10 documents the serious problems associated with subsoil compaction and raises the point that the profile and not just the surface soil must be considered. The authors draw heavily on the European literature to do an excellent job of highlighting the costs of degradation associated with subsoil compaction and advocate that a standard of no subsoil compaction should be our management goal. I'd like to call attention to their use of the least limiting water range (LLWR). This is an integrative index that expresses water content limitations associated with the available water, soil aeration and mechanical resistance. By associating properties with multiple functions, this strategy might provide a model for indicator development. The authors also propose management and prevention thresholds for tire inflation pressure where the carrying capacity of subsoil is used to determine acceptable wheel loads. They suggest that once adequate knowledge of soil strength and soil stress is known, maps for wheel load carrying capacity can be developed and also suggest that decision support systems should ideally be developed to establish the management thresholds affecting tire pressure, shape and size. Chapter 11 reviews the management's influence on soil structure, emphasizing practices that alter soil organic matter and cultural practices. Structure is discussed in relation to root growth and crop production and structure, resiliency and stability are positively related to SOM. After reviewing organic matter and disturbance as central factors influencing soil quality, the authors suggest that not enough information is available to establish either management- or indicator-based thresholds and note that for any production system, management must balance aggregate disruption with regeneration. The chapter does a very nice job of reviewing and summarizing current thinking about soil pores, including their function and response to management. Chapter 12 addresses soil erosion making an always important point about the irreversibility of soil loss. The authors review the mechanisms contributing to erosion in detail and relate losses to soil function.

There are two chapters on soil contamination (Chapters 13 and 14), with the first addressing hazards of recycling urban and industrial wastes on agricultural lands. Thresholds are proposed for potentially toxic substances (PTS) including metals, pathogens and trace organics. In addition to reviewing the traditional approach to amendments on agricultural soils, they highlight issues related to sludge recycling where PTS already have established thresholds because of their clear link to human health. The international vantage point provided calls attention to existing differences in regulatory approaches that should be considered as regulations are increasingly internationalized. Chapter 14 provides a review of pesticide effects on soil quality, including the factors influencing compound dissipation, soil characteristics affected by their application and management strategies that can be used to mitigate unintended consequences of pesticide use. The chapter is quite ambitious in its attempt to review pesticide effects on soil components and discusses their influence on soil function. The authors focus mostly on residual activity (lethality) and address both target and non-target effects. The chapter contains some novel points and raises questions that should contribute to thinking about how biotic indicators and ecotoxicology can be meaningfully applied. Clearer conclusions about which pesticides are likely to have either detrimental or benign effects could possibly have been drawn had pesticides (herbicides, insecticides and fungicides) been grouped by chemistry or mode of action. I found the discussion of organic matter's influence on pesticide sorption and persistence to be oversimplified and felt it would have been enhanced by consideration of compound solubility with respect to organic matter's partitioning characteristics.

The final group of chapters explores scientific approaches to management used in agricultural research. Chapter 15 reviews systems approaches where management strategies are to be used to manipulate ecological factors to obtain emergent properties. The authors grouped practices according to type in order to form generalizations about outcomes. This approach is consistent with the way we are likely to manage soil quality via policies or program-based mechanisms. This chapter, which draws largely from the North American literature, evaluates the soil building potential of systems including conservation tillage and organic management. It was nice to see organic management (covered here and in Chapters 9 and 17) receive attention as the best management practice alongside conservation tillage. The indicator-based focus that is

employed for thresholds in this section is consistent with the scoring function-based strategy proposed in Chapter 2. Chapter 16 explores implementation of the soil quality concept through land use planning or negotiation, which the author notes is a more appropriate term when considering decision-making made at farm or field scales. Drawing heavily from his own work, the author addresses the context in an important and aggressive manner. He suggests that scientists must improve their ability to engage in participatory interdisciplinary teams and engage in joint learning experiences. The chapter includes an ambitions attempt to define windows of opportunity associated with management thresholds. Management thresholds are argued to be more compatible with land use decision-making where consideration is made for particular soils within specific landscape contexts. I particularly liked the proposal that phenoforms of individual soil series (genoforms) which result from types of management be associated with attribute status and associated function. After making the important point that little or no information pertaining to soil and water resources is currently used in most land use decision-making processes, the author predicts that there will be world soil agreement developed in association with global trade structures within the next 10 years. The author might have noted that the International Standards Organization (ISO) already has a soil quality standard in the works that focuses primarily on persistent contaminants. This is the type of indicator or outcome-based threshold associated with environmental risk that is used when management thresholds, which do not assure outcomes, do not provide sufficient protection.

Chapter 17 provides an international perspective on the soil quality concept and its application in developing and developed countries. The author points out that constraints encountered by largely poor, resource-limited farmers in developing countries may make practices associated with low-input, organic or alternative agriculture non-sustainable. This critique of particular management types seemed to stem primarily from the use of generic management-based labels (e.g., organic) that do not necessarily refer to similar practices or outcomes when applied within different contexts. This critique points out a significant weakness in strategies that rely on management types and reminds us of an early soil quality tenet, which is that field- and farm-based approaches to soil quality and system assessment are the best. Accordingly, the author found that indicators used to assess soil quality and attendant participatory research strategies are fully appropriate for use in the developing world.

Researchers and practitioners interested in the soil quality concept will find many interesting concepts addressed in this compilation. Some will be frustrated by the fact that terms and concepts are not applied in a uniform manner throughout the text. For example, the terms 'indicator' and 'threshold' are used inconsistently throughout the book. Several authors note different scales for soil quality application but little attempt was made to segregate discussion to address spatial scale or the scale of information application (field, region, nation or globe). In order to appreciate and manage human impacts on how well soil does what we want it to do, attention should be paid to differences in how various contributors to this book have defined sustainability, as well as how these authors advocated the use or implementation of concepts related to soil quality. Examples shared in the book make it clear that common sense-, indicator-, threshold- and management-based strategies are needed to implement soil quality concepts. The editors of this book proposed a framework for discussion of soil quality in Chapter 1 and proposed major challenges in agriculture be described in scientific terms (indicators, thresholds and function) that are understood and thus managed within social and spatial contexts. While this thinking was not fully reflected in chapters included in this book, the framework proposed could provide a helpful guide for future discussions of the soil quality concept.

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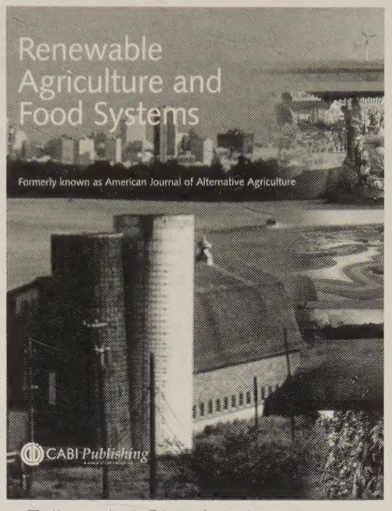

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Global Development of Organic Agriculture: Challenges and Prospects

Edited by N Halberg, H F Alroe, M T Knudsen and E S Kristensen, Danish Centre for Organic Farming, Denmark

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Readership

Researchers in organic agriculture, agricultural economics and rural development as well as NGO workers and policy makers.

Main Description

Agriculture and food systems, including organic agriculture, are undergoing a technological and structural modernisation strongly influenced by growing globalisation. Organic agricultural movements can be seen as a tangible effort towards more sustainable development. However, there are large differences between, on the one hand, industrialised farming and consumption based on global food chains and, on the other, smallholder farmers and resource poor people primarily linked in local food markets in low-income countries.

This book provides an overview of the potential role of organic agriculture in a global perspective. The book discusses in-depth political ecology, ecological justice, ecological economics and free trade with new insights on the challenges for organic agriculture. This is followed by the potential role of organic agriculture for improving soil fertility, nutrient cycling and food security and reducing veterinary medicine use, together with discussions of research needs and the importance of non-certified organic agriculture.

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1. Leopold, A. 1991. The farmer as a conservationist. In S.L. Flader and J.B. Callicott (eds). The River of the Mother of God and Other Essays by Aldo Leopold. University of Wisconsin Press, Madison, WI. p. 255–265.
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